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The Benefit of Extended Burnup in Fuel Cycle Cost

W. A. Franks, L. Geller
S. M. Stoller Corp.
1250 Broadway
New York, NY 10001

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THE BENEFIT OF EXTENDED BURNUP IN FUEL CYCLE COST

W. A. Franks and L. Geller
S. M. Stoller Corp.
1250 Broadway
New York, NY 10001

Sandia Project Monitor: A. R. DuCharme

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ABSTRACT

The benefit or cost savings associated with achieving extended discharge burnup in the light water reactors expected to operate between now and the year 2020 are estimated. The study determines the total system impact of continued DOE support for extended burnup R&D versus no further DOE support for extended burnup R&D.

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We wish to acknowledge the support and helpful interaction of Dr. Peter Lang, DOE and the important contributions to this report of our colleagues A. Strasser, L. Goldstein, and G. Stern.

Executive Summary

A study has been performed for the U. S. Department of Energy (DOE) by The S. M. Stoller Corporation under contract to Sandia National Laboratories. It estimates the benefit or cost savings associated with achieving extended discharge burnups in the light water reactors expected to operate between now and the year 2020.

This study is part of an overall cost-benefit analysis requested by the General Accounting Office. It determines the total system impact of continued DOE support for extended burnup R&D versus no further DOE support for extended burnup R&D. SMSC estimated the benefit for the front end of the fuel cycle using the mill/kwh fee as the spent fuel disposal charge. SMSC has also estimated the credit that might apply for the savings to the repository operations because of reduced fuel inventories from extended burnup.

The front end of the fuel cycle comprises: the purchase of natural uranium concentrate (U_3O_8), chemical conversion to uranium hexafluoride (UF_6), enrichment; fabrication of fuel assemblies; operation of the nuclear power plant to generate electricity, refueling of the reactor, and at-reactor-storage of spent fuel. These operations are all the responsibility of the electric utility up to the time that the spent fuel is shipped from the reactor site.

The backend of the fuel cycle comprises all the operations from the time the fuel is shipped from the reactor site until it is placed in a repository for permanent disposal or reprocessed. It includes: shipment to a monitored retrievable storage (MRS) location (if applicable), and/or the repository, storage at an MRS, and permanent disposal. These latter items are the responsibility of the federal government under the Nuclear Waste Policy Act of 1982.

In this study SMSC has developed the following:

- A projection of design discharge burnups likely to be available from the fuel fabrication vendors with and without further DOE support for extended burnup R&D.

- An estimate of the rate at which utilities will adopt these burnups was also developed.

- A set of model fuel cycles for annual and eighteen month cycles was developed for appropriate commercial operation dates over the time frame utilizing burnups consistent with the projections mentioned above.

- Unit commodity costs for U_3O_8, conversion, enrichment, fabrication, and spent fuel disposal were developed.

Using these commodity costs and the model fuel cycles, fuel cycle costs were calculated and summed over the total electrical generation through 2020 for two projections of installed nuclear capacity developed by the Energy Information Administration: the "No Future Orders" case (NFO) and "Middle Growth" case (MG). These are shown in Table E-1.

DOE has estimated the costs for the research and development program to provide new support for extended burnup as $35[1] million in as-spent dollars. In discounted 1985 dollars at a continuous discount rate of 7.813 %/year this equals $22.3 million.

Table E-2 shows the time distribution of these expenditures. This effort is intended to support new R&D projects to achieve discharge batch average burnups of 45,000 MwD/MtU for boiling water reactors (BWRs) and 50,000 MwD/MtU for pressurized water reactors (PWRs).

A benefit of $490 million (1985) dollars was found for the case of continued support for extended burnup R&D in the NFO case when only the front end components of the fuel cycle cost were considered; this value increased by 9% in the middle growth case. The benefit is the same when the backend is included as a mill/kwh fee because this fee has no impact on backend costs as burnup is increased.

Estimated savings in the no new orders nuclear growth case worth an additional $350 million and $240 million through 2020 have been computed. These are based on an alternative computation of the fee reflecting different allowances for reduced load on the waste system.

The benefits calculated for the different cases are summarized in Table E-3. These have been combined with the DOE estimated costs for R&D to calculate the benefit-cost ratio of new extended burnup R&D. The benefit-cost ratios range from 22 to 44. Table E-4 summarizes the benefit-cost ratio for each case.

TABLE E-1

Nuclear Growth Projections (2)
(gigawatts)

Year	No New Orders	Middle
1985	81	85
1986	88	94
1987	98	104
1988	104	105
1989	106	107
1990	107	111
1991	108	113
1992	108	117
1993	109	119
1994	109	119
1995	109	119
1996	109	122
1997	109	123
1998	109	123
1999	109	123
2000	108	123
2001	108	127
2002	108	132
2003	108	138
2004	108	143
2005	108	148
2006	108	152
2007	108	155
2008	108	159
2009	108	162
2010	106	166
2011	108	171
2012	99	175
2013	91	180
2014	74	184
2015	68	189
2016	60	194
2017	56	198
2018	53	203
2019	49	207
2020	49	212

TABLE E-2

Projected Research and Development Expenditures for New Extended Burnup Projects.

Year	(millions of dollars) Annual Costs
1987	6
1988	6
1989	3
1990	2
1991	3
1992	3
1993	6
1994	6
Total =	35

TABLE E-3

COMPARISON OF DIFFERENTIAL FUEL CYCLE COST (FCC) THROUGH 2020

(Millions of 1985$, Discounted To 1/85)

	No New Orders Nuclear Capacity Case			
	FCC With Mill/kwh Fee	FCC With Credit Proportional To Volume	FCC With Credit Proportional to Volume And Energy	FCC With No Disposal Charge
Net Benefit of Supporting Extended Burnup Research and Development	490	840	730	490

	Middle Growth Nuclear Capacity Case			
	FCC With Mill/kwh Fee	FCC With Credit Proportional To Volume	FCC With Credit Proportional to Volume And Energy	FCC With No Disposal Charge
Net Benefit of Supporting Extended Burnup Research and Development	550	980	840	550

TABLE E-4
COMPARISON OF BENEFIT-COST RATIO OF EXTENDED BURNUP R&D

	Benefit-Cost Ratio With Mill/kwh Disposal Fee	Benefit-Cost Ratio With Credit Proportional to Volume Reduction Due To Extended Burnup*	Benefit-Cost Ratio With Lesser Credit Proportional to Volume Reduction Due to Extended Burnup**	Benefit-Cost Ratio Considering Only Front-End Benefits
No New Orders Nuclear Capacity Case	22	38	33	22
Middle Growth Nuclear Capacity Case	25	44	38	25

* Proportional to $/kgU.

** Proportional to $/kgU + $/MwD.

1.0 Introduction

In September of 1984 Sandia National Laboratories under contract to the Department of Energy (DOE) authorized the S. M. Stoller Corporation to perform an analysis of the fuel cycle cost benefits of continued extension in discharge burnups. SMSC's assignment was to develop the parameters for the front end of the fuel cycle and compute the fuel cycle cost savings.

The SMSC work is an extension of its studies that had been performed for the Electric Power Research Institute (EPRI)[3]. They investigate the optimum fuel cycle cost as a function of burnup by using fuel cycle unit costs typical of those currently employed by utilities.

This study was performed based on equilibrium fuel cycles and out-in fuel management for PWR's and scatter-load for BWR's. The current study is extending this work by treating the transition effects in fuel cycle cost as extended burnups are achieved and also low leakage fuel management as it is implemented in PWR's.

SMSC has developed a projection of the rate of adoption of extended burnups by utilities under two scenarios:

(1) The design burnup has been projected assuming no further DOE support of extended burnup development programs beyond completion of existing projects.

(2) New DOE support is assumed.

Fuel cycles characteristic of burnups for both PWRs and BWRs have been developed. Fuel cycle costs as a function of time for the two burnup scenarios have been computed. These fuel cycle costs have been combined with projections of installed nuclear capacity developed by the Energy Information Administration (EIA) to compute the nationwide cost savings associated with extended burnups.

This report is divided as follows: Section Two describes the fuel cycle unit costs employed. Section Three reports on the analysis performed to project the levels of extended burnup achieved over time. Section Four describes the fuel cycle cost analysis in detail. Section Five presents the conclusions of the study.

Three appendices are incorporated. The first appendix describes the formulation of the three charges for spent fuel disposal used in this study. The second describes the impact of extended burnup on fuel assembly structural components to assess whether there is a fuel handling problem at extended burnup. It concludes that based on currently available data there should not be. The third appendix describes the fuel cycle cost calculation methodology.

2.0 Unit Cost Projections

The unit cost projections developed for the EPRI study[3] have been extended to the year 2020. Those projections were developed by surveying 15 EPRI member utilities for current unit costs and general inflation groundrules. Nine utilities provided current dollar price projections for 1983 to 1995. They included a projection of the anticipated general inflation rate for the same period.

The unit price projections were then reduced by deflating each utility's current dollar projection (using that utility's general inflation projection) to obtain a price projection for 1984 to 1995, in mid-1984 dollars. The constant dollar price projections through 1995 were developed by averaging the individual utility constant dollar values for each year. Projections beyond 1995 were established by extending the 1995 values.

Estimates were also developed for the fabrication price adders appropriate for extended burnup designs. These were developed on the basis of:

(1) our insight into the fabrication market;

(2) the utility surveys from the EPRI study; and

(3) SMSC analysis of the costs of fabricating nuclear fuel.

The base designs (current technology) are intended for service with design discharge exposures in the mid 30 MwD/kgU range for BWRs and in the high 30's and low 40's for PWRs.

Also considered were possible price adders for design modifications required to go beyond this range. These include barrier fuel, new types of burnable absorbers, and increased plenum volume that reflect possible changes required for extended burnup designs. A 15% increase for BWR fuel fabrication cost covered this.

Furthermore, both the PWR and BWR fabrication prices were increased by one half the proportionate increase in burnup. This reflected the decrease in vendors' shop load (inversely proportional to the burnup). It was reduced to reflect competitive pressures.

On the other hand, these projections of fabrication price adders may be conservatively high as the diminished demand for fabrication associated with extended burnup may reduce the vendors' shop load. These are, or may be, overloaded.

These price projection are conservative in another regard. Extended burnup decreases U_3O_8 requirements in the future. This can have a depressing effect on prices. (Figure 2-1 shows a graph of cumulative demand versus marginal sales price.) Since with extended burnup there is less cumulative demand the marginal sales price is lower. If supply and demand were equal U_3O_8 prices would be lower than without extended burnup.

Two other formulations for waste systems cost savings associated with extended burnup were used. The first is based solely on the total spent fuel mass generated at a plant; the second assumes the charge to be a function of the heat content (burnup) and weight of generated spent fuel.

These formulations were normalized so that they gave the same total charge as the mill/kwhr fee in the case of a PWR discharging fuel at a burnup of 33 MwD/kgU. The split in the combined charge ($125/kgU and $3.78/MWD) was based on a 50/50 proportion of the waste system costs that were volume dependent and energy (burnup) dependent. While this is simplified, it represents an approximation for the current disposal designs. (The development of these fee formulations is described in Appendix One.)

The computed savings are simply the difference between the back-end charge using the mill/kwh fee and the back-end charge computed with either of the two formulations described above.

Table 2-1 shows the unit costs developed for this study and documents the assumptions used. These costs are in constant 1/1/1985 dollars. As discussed in Section 4.0, all the computations have been done in constant 1/1/1985 dollars, discounted to reflect the utilities' money costs.

These unit cost projections reflect the average costs experienced by U.S. utilities. Clearly from the data in reference 3, there is a range of costs experienced and a range of future costs.

Based on our own analyses we find that these average costs are consistent with the values we at SMSC develop through independent estimates. Therefore, the fuel cycle costs based on these projections are reasonable ones for performing benefit-cost analyses.

TABLE 2-1

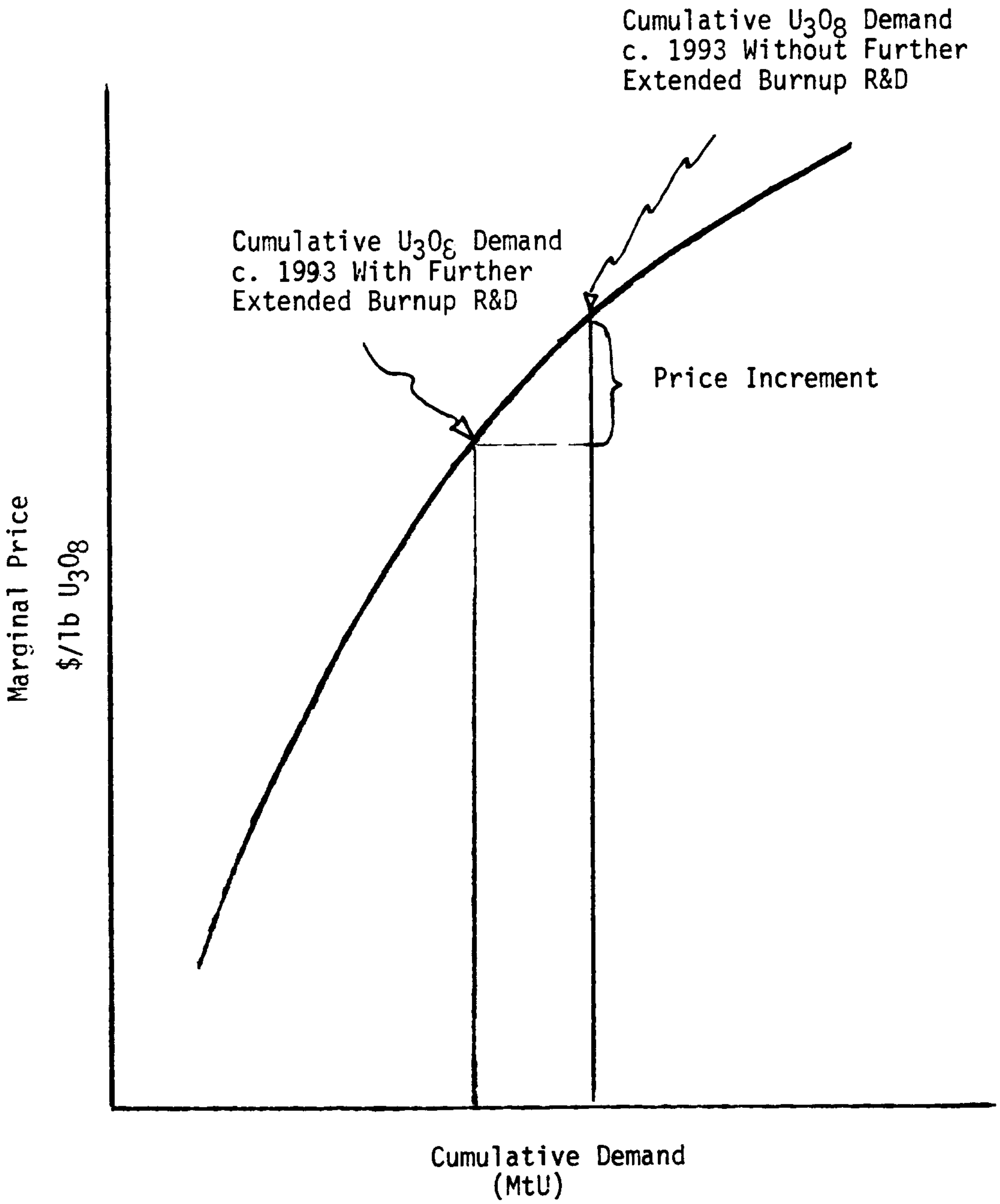
WORKING VALUES OF UNIT COSTS

YEAR	U308		Conversion		Enrichment	Fabrication, $/kgU					Spent Fuel Disposal		
	$/lb		$/kgU		$/SWU	BWR		PWR			Current Basis	Constant Mass	Burnup Dependent
	(a)	(b)		(b)	(d)	(e)	(f)	(g)	(h)	(i)			
1985	29	30.5	7(a)	7.4	135	230	265	230	245	273	$1000/GWh(e)	$250/kgU	$125/kgU+$3.78/MwD
1990	42	44.2	7(a)	7.4	135	230	265	230	245	273	$1000/GWh(e)	$250/kgU	$125/kgU+$3.78/MwD
1995	49	51.6	7(a)	7.4	135	230	265	230	245	273	$1000/GWh(e)	$250/kgU	$125/kgU+$3.78/MwD
2000	49	51.6	9(c)	9.5	135	230	265	230	245	273	$1000/GWh(e)	$250/kgU	$125/kgU+$3.78/MwD

(a) Source: EPRI Research Program 1577-1. Values are 1983 dollars, Mid-range Case.
(b) Converted to 1/1/85 dollars by factor 1.0526=(GNP Deflator 1/1/85)/(GNP Deflator 1983)
(c) Smoothed average value based on new capacity added
(d) The EPRI Study used 140, 136, 132, in 1985, 1990, 1995 resp., in 1983 dollars.
SMSC studies suggest $135/SWU in 1985 dollars is a reasonable basis for cost estimating
(e) For burnups <=33 MWD/kgU
(f) For burnups in range 33<B<=45
(g) For burnups <=40 MWD/kgU
(h) For burnups in range 40<B<=50
(i) For burnups >50

FIGURE 2-1

Conceptual Relationship Between
Marginal Price and Cumulative Demand



3.0 Projections of Extended Burnup

3.1 Potential Technical Limitations to Extended Burnup

SMSC had to develop estimates of discharge burnups through the year 2020, based on its best judgment. SMSC reviewed, updated, and evaluated its data base in the following areas:

- Extended burnup levels achieved and experience with lead test assemblies (LTAs) and reload batches of fuel.
- Projection of extended burnup experience expected.
- Current and expected commercial fuel warranties for extended burnup.
- Potential technical limits to extended burnup, including parameters related to thermal-mechanical design, nuclear design, and fuel storage.
- Current and potential licensing issues related to extended burnup.

The data of five vendors were included: Combustion Engineering (PWR), Westinghouse (PWR), Exxon Nuclear (PWR and BWR), Babcock & Wilcox (PWR) and General Electric (BWR). Experience in Europe was also considered.

To reach higher discharge burnup levels, fuel assemblies will have to meet increasingly severe thermal-mechanical performance requirements. This is due to higher fuel burnup, higher neutron exposure of structural components, and longer exposure time of the assembly to the coolant temperatures and chemical environment. These requirements will have to be met by changes in the design and fabrication methods.

The affected parameters are listed below in approximately decreasing order of importance:

-- Zircaloy growth
-- Zircaloy corrosion
-- Internal rod pressure

The items above are more sensitive to extended burnup; they are predicted to increase at least linearly with increased burnup. The items below are less sensitive to extended burnup; they are predicted to increase at a lower rate than the burnup.

-- Effect of radiation on properties
-- Effect of stress-corrosion assisted and mechanical pellet clad interactions (pci-s)
-- Spacer spring relaxation

Extended burnup also requires higher reload enrichments and excess reactivity at the beginning of cycle. This tends to complicate the cycle design, increase power peaking and potentially reduce margins.

SMSC reviewed the potential technical limitations to extended burnup. To date the only generic cause for a limit has been the differential growth of Zircaloy. The reasons for under-predicting the limits due to Zircaloy growth have been the wide statistical spread of the data, lot to lot variability, and other variables.

The limits can be raised significantly by modifying the mechanical design of the assembly and the fuel rod. This has been accomplished or is in process at most vendors.

Other potential limits to burnup are believed to be:

- Zircaloy corrosion
- Internal rod pressure
- Effect of radiation on Zircaloy properties
- Pellet-clad interactions

- Spacer spring relaxation
- Nuclear peaking (thermal margins)
- Source term

The review indicates that experience has not yet reached these limits from burnup alone. (For example, corrosion limits have been reached due to poor water chemistry, marginal Zircaloy quality and burnup; however, this is not considered by SMSC as a true burnup limit.) Nevertheless, these are still the likely limits at burnups higher than achieved to date. The actual conditions and burnup levels at which these parameters may become limiting are difficult to predict and must be established by monitoring of extended burnup fuel.

Regarding the nuclear design, transition cycles from lower to higher discharge exposure present the most difficulty in designing to meet peaking limits. On the average, during a cycle there will be a margin reduction to the design limit(s) with extended burnup operation. This possibly could produce a loss in capacity factor.

Operation to burnups beyond those which will allow meeting current design limits can be accomplished by enhancing the design and/or operating limits. Margin recovery techniques and/or fuel design modifications would be required for such enhancement.

A summary of the relationship of the limits to current experience is given in Table 3-1 for BWRs and Table 3-2 for PWRs. Design predictions are given in parentheses. Except for Zircaloy growth, good experience exists for most performance parameters with lead test assemblies to equivalent batch average exposures of 34 MwD/kgU for BWR fuel, and 47 MwD/kgU for PWR fuel.

3.2 Extended Burnup Experience and Projection

3.2.1 Introduction

Experience with extended burnup fuel in the U.S. is being developed both in individual utility sponsored efforts and in programs at several utilities supported by the U.S. Department of Energy, Electric Power Research Institute (EPRI), and Empire State Electric Energy Research Company (ESEERCO).

For non-U.S. vendors, many programs have been conducted individually between the vendor and a utility.

3.2.2 Extended Burnup Experience in the U.S.

The burnup experience information available from all the U.S. fuel vendors for product line fuel was reviewed and consolidated to present an overview of the situation. These vendors are:

PWR

Babcock and Wilcox (B&W)*
Combustion Engineering (CE)
Exxon Nuclear (ENC)
Westinghouse (W)

BWR

Exxon Nuclear (ENC)
General Electric (GE)

---

* The B&W data base does not include fuel fabricated under B&W license for W licensed PWRs operating in Japan.

The experience base is dominated by W for the PWR and GE for the BWR: W has fabricated 45-50% of the PWR rods made by U.S. vendors which have been or are being irradiated; General Electric has fabricated about 90-95% of the irradiated BWR rods made by U.S. vendors.

Figure 3-1 and Tables 3-4, 3-5, and 3-6 summarize the composite information. Figure 3-1 shows thousands of irradiated PWR fuel rods fabricated by U.S. vendors vs. burnup. In total, about 5.7 million PWR fuel rods or about 28,000 assemblies have been or are under irradiation. About 2.4% of these rods or roughly 675 assemblies successfully have achieved extended burnup exposures, beyond 36 MwD/kgU.

Table 3-4 summarizes U.S. BWR vendor experience with product line fuels. About 2.25 million BWR fuel rods or roughly 36,000 assemblies have been or are under irradiation. A small fraction of these, probably about 1-2 percent, has achieved extended burnups in the 30-46 MwD/kgU range. Table 3-5 summarizes the PWR data from figure 4-1 in the same format as Table 3-4 for the BWR's.

Table 3-6 presents the maximum lead test assembly burnups of U.S. vendor product line fuels. Lead burnups for PWR assemblies range up to 55 GWD/MTU and for BWR assemblies up to 46 MwD/kgU.

3.2.3 Projections of Extended Burnup

Using the information presented in the preceding sections we developed an estimate for the average discharge burnups from U.S. LWR's from 1984-2020.

The values were developed in two steps.

1. Judgments were made about when sufficient information on fuel performance might be available to allow fuel suppliers to design and warrant fuel assemblies of increasingly higher burnups.

These values are shown under the headings for PWR and BWR "maximum batch MwD/kgU that might prudently be expected from fuel loaded in year" of Table 3-3.

2. Additional judgments were made about the rate at which utilities might elect to use these extended burnup fuel assemblies. These values are given under the headings "average utility selection" in Table 3-3.

Two possibilities were considered for achieving extended burnups:

1. No new DOE support for R&D.
2. A full program of support.

The estimated burnup values in either case are shown on the two sides of the "slashes" in Table 3-3, one column for PWR and the other for BWR.

The judgments as to when sufficient information would be available to allow vendors to design and warrant fuel assemblies of increasingly higher burnups were based on:

1. The status and burnups achieved in current lead test assembly and extended burnup programs
2. The length of time it would take to develop similar information at higher burnups.

For instance to achieve burnups of 50 to 60 MwD/kgU in a PWR requires five to six years, respectively, of operation. It was assumed that these programs would be initiated and conducted more efficiently with continued R&D support.

In developing these numbers we have considered:

1. The data on current fuel experience discussed in this report. We gave significant weight to the good experience that has been accumulated with lead test assemblies.

2. Several PWR vendors have current design burnup goals in the 45-48 MwD/kgU range.

3. Some BWR manufacturers are currently prepared to warrant their advanced fuel under some circumstances to 36 MwD/kgU.

TABLE 3-1
SUMMARY OF POTENTIAL LIMITATIONS - BWRs

Parameter	Burnup Experience (MwD/kgU) Rod	Assembly	Equiv. Batch	Remarks
Zircaloy Growth		34	28.5	Limit for GE6 design
Zircaloy Corrosion	45		34	No limit at this level. SMSC estimates 45 batch average may be achievable.
			($\geq$34)	Heat treated clad is expected to have higher limits.
Internal Fuel Rod Pressure	45		34 ($\geq$34)	Data on unpressurized fuel GE (design) is higher. The limit is unknown.
PCI - Ramp Tests	33		25	Unpressurized standard fuel. Poor performance at standard PCIOMRs.
	24		18	Unpressurized and Pressurized Zr barrier fuel - Good performance has been experienced.
			($\geq$34)	(Design). Performance of advanced BWR fuels expected to be good. High burnup achievable with operating restrictions if that becomes necessary.
Zircaloy Properties	42		32	No limit at this level. SMSC estimates higher levels achievable, but are dependent on rate of further ductility loss with burnup.
Spring Relaxation		45	38 32	Inconel spring relaxation is saturated and satisfactory. No limit reached.
Nuclear Peaking			($\geq$34)	(Designs) by vendors appear satisfactory. Thermal limits may have to be raised (use of barrier fuel is required to achieve this)
Source Term				No generic limits at current burnup levels, and none expected at extended burnups.

*The values in parentheses and the word (Design) refer to the capabilities of new or improved designs currently being offered by the vendors. Since the actual values are proprietary they are indicated as being $\geq$ the current experience levels.

TABLE 3-2

SUMMARY OF POTENTIAL LIMITATIONS - PWRs

Parameter	Burnup Experience (MwD/kgU) Rod	Assembly	Equiv. Batch	Remarks
Zircaloy Growth				
15x15, W		55	47 (>47)	One rod reached limit. SMSC estimated (Design) limit for new designs.
14x14, CE	55	52	45	Considered reasonable limit.
17x17, W	45		37	Current limit of experience. Performance is ok. Estimated to be as good as 15x15.
16x16, CE			28 (≥38)	Limit reached prematurely. (Design) is under development.
Zircaloy Corrosion	59		49	No limit at this level. SMSC estimates 58 batch average may be achievable without heat treated clad for standard temperature plants.
Internal Rod. Pressure	50		42	No limit at this level. SMSC estimates 58 batch average may be achievable.
PCI - Ramp Tests	43		35	Generally good performance. High burnup achievable with operating restrictions, if that becomes necessary.
Zircaloy Properties		55	47	No limit at this level. SMSC estimates higher levels achievable dependent on rate of further ductility loss with burnup.
Spring Relaxation				
Inconel		55	47	Relaxation saturated and satisfactory.
Zircaloy	55		45	Satisfactory performance, but almost no quantitative data. Difficult to estimate additional potential.
Nuclear Peaking			40 (45)	No limit reached. (Design) satisfactory.
Source Term				No generic limits at current burnup levels, and none expected at extended burnup.

*The values in parentheses and the word (Design) refer to the capabilities of new or improved designs currently being offered by the vendors. Since the actual values are proprietary they are indicated as being ≥ the current experience levels.

TABLE 3-3

Design Burnup Evolution

Year	PWR: Maximum batch MwD/kgU that might prudently be expected from fuel loaded in year — Without New DOE R&D	PWR: Maximum batch MwD/kgU that might prudently be expected from fuel loaded in year — With New DOE R&D	PWR: Average Utility Selection — Without New DOE R&D	PWR: Average Utility Selection — With New DOE R&D	BWR: Maximum batch MwD/kgU that might prudently be expected from fuel loaded in year — Without New DOE R&D	BWR: Maximum batch MwD/kgU that might prudently be expected from fuel loaded in year — With New DOE R&D	BWR: Average Utility Selection — Without New DOE R&D	BWR: Average Utility Selection — With New DOE R&D
1984	45	45	39	39	32-33	32-33	31	31
1990	47	50	40	45	36-38	38-40	35	38
1995	50	55	45	50	36-40	40-42	38	40
2000 and beyond	50	60	50	55	38-40	42-45	38	43

TABLE 3-4

U.S. BWR VENDOR EXPERIENCE-PRODUCT LINE FUELS

No. of Fuel Rods Irradiated	-	2,229,000
Highest Reload Batch Average Burnup, MwD/kgU	-	31.1
Highest Bundle Average Burnup, MwD/kgU	-	45.8

TABLE 3-5

U.S. PWR VENDOR EXPERIENCE-PRODUCT LINE FUELS

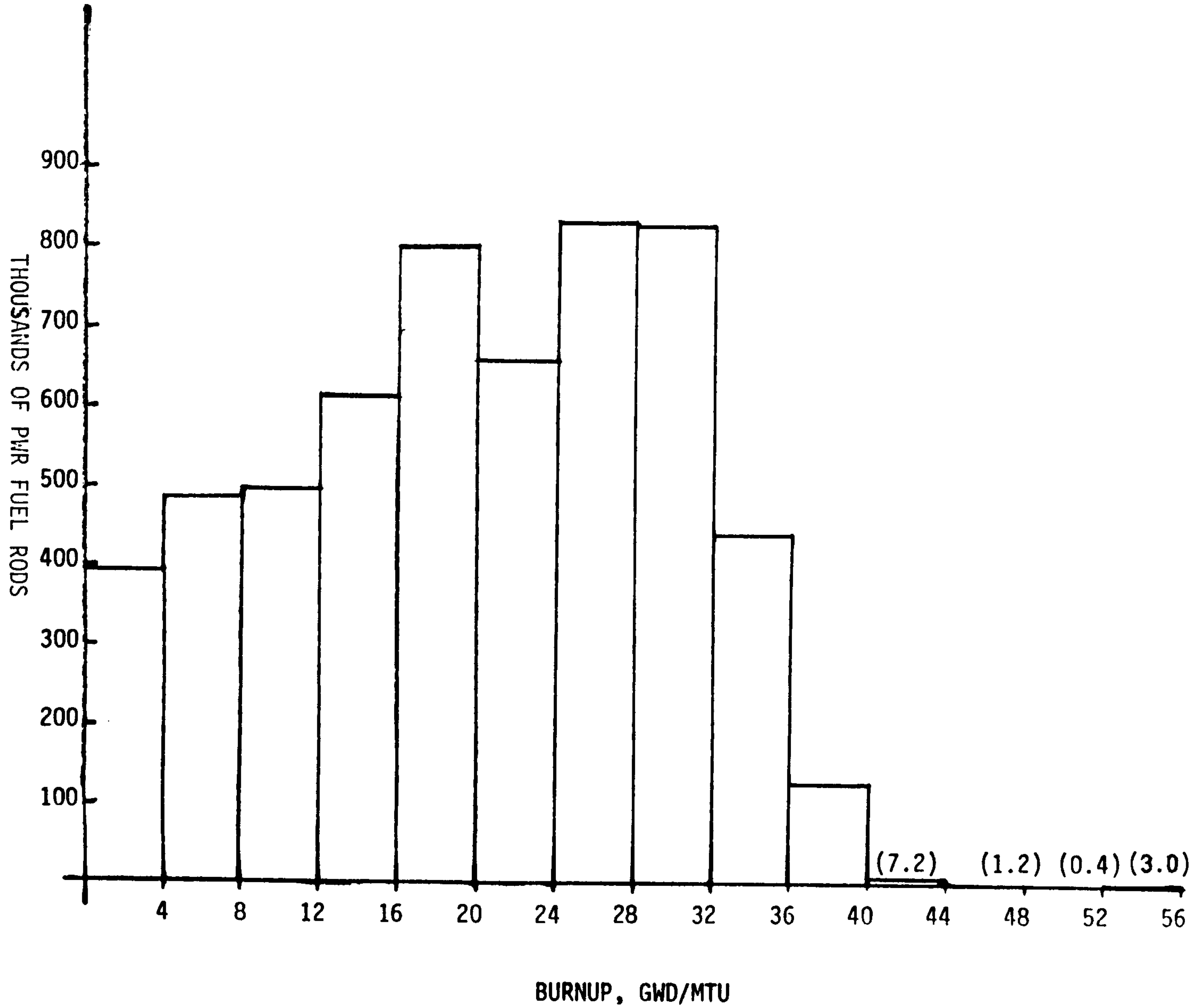
No. of Fuel Rods Irradiated	-	5,700,000
Highest Reload Batch Average Burnup, MwD/kgU	-	40[4]
Highest Bundle Average Burnup, MwD/kgU	-	55

TABLE 3-6

MAXIMUM LEAD TEST ASSEMBLY BURNUPS OF U.S. VENDOR PRODUCT LINE FUELS

REACTOR TYPE	NO. OF ASSEMBLIES IN EXTENDED BURNUP RANGE	RANGE, MwD/kgU
PWR	11	42.5 - 54.8
BWR	14	35 - 45.8

FIGURE 3-1 CONSOLIDATION OF US VENDOR, PWR FUEL EXPERIENCE AS OF 1983



4.0 Analysis of Fuel Cycle Cost Benefit for Extended Burnup

4.1 Introduction

The component of fuel cycle cost due to "Front-End" expenses has been computed in pairs for each of the individual life cycles described in Section 4.3.1 below. A pair consists of one life cycle assuming no new R&D and another life cycle assuming new R&D. All other assumptions remain the same. The difference between the fuel cycle costs of the components of a pair measures the expected benefit due to new R&D.

These differential fuel cycle costs were then used with the Nuclear Power Growth projections supplied by EIA. This determined the total "Front-End" benefit due to continued R&D for the USA through 2020.

In addition, we examined the impact of going to higher burnups on the "Back End" costs. We used the current mill/kwhr prescription and two hypothetical calculational approaches for the possible savings as described in Section 2.0 and Appendix 1.

The following description of the analysis treats each of the many variables affecting front-end and back-end costs independently.

4.2 Definition of Fuel Cycle Costs

In this study, the cost associated with the supply of fresh fuel (Front-end Fuel Cycle Costs) and the disposal of spent fuel (Back-End Fuel Cycle Costs) is defined as:

- The Present Worth over the period 1/1/85-12/31/2020 of all the revenues needed to recover the required investments and to pay the money costs (including income taxes) on unrecovered investments.

Each batch is treated as a separate investment. Its required revenue is assumed to be continuously collected at a constant rate during the time it is expected to be in-core.

This uniform stream of payments is continuously discounted to 1/1/85 at a continuously compounded rate. The result is the present worth of future revenue requirements (PWFRR) for either the Front-End or the Back-end for that batch.

The sum of the present worths for all batches is the "Fuel Cycle Cost." See Appendix 3 for details.

Any revenues required to be paid before 1/1/85 or after 12/31/2020 are ignored. All plants are assumed to have operating lifetimes of 30 years. Those now operating which started up before 1980 are assumed to continue operating until 1/1/2010.

4.3 Fuel Cycle Costs

4.3.1 Reactors and Fuel Designs Treated

Lifetime fuel cycles for a Reference BWR and a Reference PWR were developed for this study. The pertinent characteristics of each of these reactors is given in Table 4-1.

For each reactor, 16 different life histories were developed in accordance with the parameters shown in Table 4-2. A full lifetime history was developed to avoid the usual practice of comparing only the equilibrium benefits of higher discharge burnups. Effects due to the transition from one target burnup to another over successive operating cycles have an important impact on the net benefits to be expected from extended burnups. These are included in this analysis.

Regarding the values selected for Table 4-1, they are meant to represent typical values for U.S. reactors of each type, normalized to a net output of 1068 MWe. The BWR uses 8x8 fuel assemblies with 2 water rods and gadolinium burnable absorber. Natural uranium "blankets" at each end are included. This is current practice, as it is for most BWR's to plan for a "coastdown" at the end-of-cycle; some go for more than the 50 Full-Power-Days (FPD's) allowed here.

The PWR fuel uses an "optimized" 17x17 array and an advanced annular burnable absorber design. The PWR fuel in-core loading pattern is placed to reduce the normal out of core leakage (low-leakage fuel management, LLFM). One objective of this study is to determine how the advantage for higher burnups found in a previous study[3] is affected when an out-in fuel management strategy is replaced by LLFM.

Regarding the parameters selected in Table 4-2, Parameter 1 was used because we are seeking the benefit that may accrue nationally from burnup extension. We need to include estimates for operating reactors, those in the construction pipe-line, and those yet to be built.

Parameter 2 was introduced because reactors operate on various cycle lengths, each one trying to optimize within their own constraints. Longer cycle lengths lead to higher nuclear fuel costs. Despite this, many utilities use longer cycles because they believe the cost savings from reducing the refueling outages and the possibility of higher overall capacity more than compensates. This is particularly true since there is a synergism between higher fuel discharge burnup and longer operating cycle length that reduces the fuel cycle penalty associated with going to longer cycles.

In our analysis we have assumed that a reactor is either on a 12 month or on an 18 month cycle and that any reactor operating on a cycle of intermediate length can be adequately represented by a mixture of the other two. It is possible that many BWR's will go to 24 month cycles (there are a few already). In this case our estimate for the benefits of higher burnup may be on the low side.

Parameter 3 deals with the heart of the study. Each schedule consists of target burnups defined as a function of time. We assume that the target burnups for any fuel a fuel manufacturer will deliver in the following year would be set on this basis. The rationale for these burnups is given in Section 3.

Representative fuel cycle histories are given in Tables 4-3a to 4-3f. These histories were developed using the SMSC reactivity program PLACEM.

This program employs analytical fits to inverse-k_∞ data generated as CASMO outputs for a range of charge enrichments, burnups and fuel types. These fits characterize the reactivity state of a fuel batch.

The reactivity state of the core is found by mass-weighting the batch reactivities. The end of an operating cycle occurs when this core reactivity equals an end-of-cycle reactivity based on fits to integral data available to SMSC.

4.3.2. Equilibrium Fuel Cycle Costs

Before calculating overall general benefits, the front-end fuel cycle costs as a function of burnup for the reference reactors in Table 4-1 were calculated for the equilibrium state. This was to see whether an optimum burnup exists, also whether the burnup schedules in Table 4-2 (which were primarily based on what the technology might permit in the future) are economically desirable. Both 12 and 18 month cycles were considered.

Figures 4-1 to 4-4 show the results of these calcuations.

In calculating the lifetime fuel cycles for the Reference Reactors, the target burnup that would be technically available for fuel charged in each year was first found from Table 4-2. This "Nominal" Target Burnup was taken as a maximum.

The actual target burnup used was taken to be the largest value not exceeding the Nominal Target Burnup and which under equilibrium conditions would be consistent with the requirement that the batch size be a multiple of 4.

This "Compatible" Target Burnup is usually 2-3% below the Nominal Target Burnup for BWR's and 3-6% for PWR's. If batch sizes are not required to be a multiple of four the compatible burnups are much closer to the Nominal Target Burnups.

The unit costs used for uranium, conversion and enrichment were generally the 1990 values shown in Table 2-1. However, several runs were made with uranium at \$25/lb U_3O_8 and conversion at \$5/kgU. Although these lowered the level of the costs by 22% they did not significantly alter the shape of the curves. This would also lower the savings by approximately the same amount, but they would still be significant. This is shown in Figure 4-5.

In the preceding study(3) for EPRI extensive sensitivity studies were performed varying all the fuel cycle commodity and carrying costs individually for PWR and BWR, 12 and 18 month cycles. This shifted the levels of the costs similarly to that described above. The shapes of curves changed only slightly.

Increases in fuel burnup may require technical modifications to the fuel designs that increase fabrication costs, such as increased fission gas plenum volume or special burnable absorber designs. It will also:

- reduce the load on the fuel fabrication vendors manufacturing facilities so that manufacturers will have to amortize their fixed costs over a smaller volume or:
- reduce the demand so that additional fabrication plants or manufacturing lines may not be required.

An estimate of increased fabrication prices was described in Section 2. Because of possible increased fabrication costs, two cost schedules were used. In the first the cost was kept constant at \$230/kgU; in the second, it was allowed to increase with target discharge burnup, in accordance with the values shown in Table 2-1. The continuous discount rate used was 7.813%/year.

On Figures 4-1 through 4-4 we have plotted the percentage change in the Fuel Cycle Cost, from the lowest "compatible"* target burnup considered: 32.2 MwD/kgU for the PWR; and 27.8 MwD/kgU for the BWR. Also plotted is the percentage change in the Fuel Cycle Cost from one compatible target burnup to the next higher one.

For all cases, fuel cycle costs were lowest for the highest burnup run. However, the PWR on a 12 month refueling cycle shows little benefit from increases after a burnup of around 50-55 MwD/kgU. On an 18 month cycle the PWR shows a greater benefit from higher discharge burnups, suggesting an optimum at around 55-60 MwD/kgU.

The BWR gained even more than the PWR from increased discharge burnups, with the 18 month cycle, again showing an enhanced benefit. We conclude that the burnup schedules given in Table 3-3 and used as the basis for our primary results are consistent with keeping fuel cycle costs at their minimum.

The impact on the equilibrium back-end fuel cycle costs of extended burnup was next examined. Figure 4-6 shows a relative plot of this component of the total fuel cycle cost for either type of LWR for the three different formulations of the credit calculation discussed earlier in Section 2. The credit is the difference between the line marked mill/kwh fee and either of the two others marked respectively $/kgU and $/kgU + $/MwD.

In each case the PWFRR was found by assuming a continuous collection of revenues over the lifetime of a batch. The total collected was determined by the batch characteristics and unit disposal costs.

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* Compatible target burnups are achieved with batch sizes that are divisable by four. Since the batch sizes change by whole integers only discrete burnups can be obtained for a given cycle length.

The base assumed was the mill/kwh fee. This is the invariant level line in the figure. The component does not vary with burnup because the fuel cycle cost associated with the mill/kwh fee depends only upon the energy generated. This is constant in all these cases; the total energy generated does not vary with burnup.

The first alternative credit structure examined was dependent only on the kilograms of uranium in the fuel assembly to be disposed. This is the lowest curve in the exhibit. It is proportional to the kilograms of uranium charged to the reactor. Since fewer kilograms are charged at higher burnups, this curve diminishes with increasing burnup.

The second alternative credit structure is a combination of a $/kgU and a $/MwD charge. In an equilibrium cycle at a burnup of 33 MwD/kgU for the fee selected the $/MwD charge is exactly half of the mill/kwh fee. Hence, this third credit structure would be intermediate between the other two.

Both alternate formulations have been defined to result in equivalent costs to the mill/kwh fee at 33 MwD/kgU.

4.4 EIA Projections of Installed Nuclear Capacity

The DOE Energy Information Administration (EIA) provided two projections of installed nuclear capacity for use in this analysis. These are shown in Table 4-4.

The first was the No-New Orders case. This case assumes no new orders for nuclear generating capacity and no further cancellations of projects currently underway.

The second projection is the EIA Mid-case projection. This assumes modest additional growth in installed capacity starting beyond the year 2000.

4.5 Calculation of the Fuel Cycle Cost Benefit for the Country - 1985-2020

We computed the differential present worth in 1/85 dollars of the fuel cycle cost for all installed capacity in the USA through the year 2020. This was developed using the following assumptions.

1) The mix of PWR to BWR plants is 2 to 1 and will remain so through 2020.

2) 68% of the most recently operated cycles in BWRs are long cycles (365 full power days or longer). We assumed that for BWRs, 68% of the fuel cycle cost would be contributed in 1985 using the costs for the 18 month fuel cycle developed for this study. The balance is contributed by the 12 month fuel cycle cost which is used to represent all cycles shorter than 365 full power days.

We also assume that the proportion of long cycles for BWRs would increase to 90% by 1990 and remain constant thereafter. This recognizes:

- The trend to longer cycles
- That several plants cannot (because of system considerations) or will not (for other reasons) shift to a longer cycle.
- That extended burnup is synergistic with longer cycles
- That one of the reasons for going to extended burnup is to permit simpler fuel management in longer cycles.

For PWRs the proportion of long cycles is currently 50%. We assumed that it would increase to 75% by 1990 and remain constant thereafter. Figure 4-7 shows the proportion of long and short cycles versus time. Figures 4-8 and 4-9 are plots of the differential between No New R&D and New R&D, present worths of the pairs of fuel cycles considered. For each reactor type and cycle length the four calculated differentials at the start-up year, 1980, 1985, 1990, 2000 have been joined.

Using the projections of installed capacity provided by EIA given in Table 4-4, the total differential fuel cycle cost was computed through the year 2020. Table 4-5 show the cumulative differential fuel cycle cost for each of the installed capacity scenarios provided by EIA; also for each credit case developed by SMSC for reduced repository costs associated with extended burnup. These are the benefits associated with each of the R&D scenarios and the different credit treatments.

The procedure for computing the total differential fuel cycle cost was:

1. A composite cumulative differential fuel cost ($\Delta FCC(N)$) was calculated using the weighting factors described earlier. This can be written as follows:

   $\Delta FCC(T, C, N)$ = The present worth of the differential fuel cycle cost for operation from 1985 through 2020 of a reactor of type T starting operation in year N on cycle type C.

   N = 1980, 1985, 1990, 2000
   T = PWR or BWR
   C = 18 or 12 month cycle

   $W_1(T,N)$ = The fraction reactor type T installed in year N

   W_1 (BWR, N) = .33

   W_1 (PWR, N) = .67

   W_2 (T,C,N) = The fraction of reactors of type T operating on cycle C in year N

   W_2 (BWR, 18 months, 1985) = 0.68
   W_2 (BWR, 18 months, 1990 and beyond) = 0.90
   W_2 (BWR, 12 months, 1985 = 0.32
   W_2 (BWR, 12 months, 1990 and beyond) = 0.10

W_2 (PWR, 18 months, 1985) = 0.50
W_2 (PWR, 18 months, 1990 and beyond) = 0.75
W_2 (PWR, 12 months, 1985) = 0.50
W_2 (PWR, 12 months, 1990 and beyond) = 0.25

$$\Delta FCC(N) = \sum_T W_1(T,N) \sum_C W_2(T,C,N) \times \Delta FCC\ (T,C,N)$$

Δ FCC (N) for intermediate dates was found by linear interpolation between the values for 1980, 1985, 1990, 2000, and 2020. The ΔFCC (2020) = 0 by definition

2. For each year from 1985 to 2020 the incremental increase in nuclear generating capacity $\Delta P(N)$ was computed from the EIA projections.

3. The total differential fuel cost then was computed

$$\Delta FCC = \sum_N \Delta P(N) \times \Delta FCC(N)$$

These are the values displayed in Table 4-5. The benefit-cost ratio (Table 4-6) for continued R&D was computed by dividing the present worth of DOE expenditures for high burnup into the total fuel cost differential. The total DOE R&D expenditures and the present worth are shown on Table 4-7. These were provided independently by DOE[1].

TABLE 4-1

CHARACTERISTICS ASSUMED FOR THE REFERENCE LWR's

	BWR	PWR
Core Thermal MW	3390	3390
Net Electric MW	1068	1068
Fuel Assembly Core Lattice	Assymetrical for plants starting up before 1985 Symmetrical for plants starting up in 1985 and thereafter	Symmetrical for all plants
Amount of Planned Cycle Extensions ("coastdown")	50 full-power days each cycle except the first	None
Number of Fuel Assemblies in the core	744	193
kgU/Fuel Assembly	182.3	420.8
Fuel Assembly Description	8x8 array including 2 water rods, gadolinia in rods as needed, 6" natural uranium blankets at each end	17x17 array, separate annular boron absorber rods as needed, "wet" lattice
Fuel Management	Scatter reloading	Low leakage reloading
	The number of fuel assemblies in each batch is divisible by 4.	The number of fuel assemblies in each batch is divisible by 4.
	Enrichments rounded upward in the second decimal place.	Enrichments rounded upward in the second decimal place.

TABLE 4-2

PARAMETERS DETERMINING THE NUMBER OF LIFE HISTORIES CALCULATED

Parameter 1

Commercial operating date. Four values were used: 1980, 1985, 1990, 2000.

Parameter 2

Equilibrium cycle length. Two values were used: A "shorter" cycle length, and a "longer cycle length". These, together with other related assumptions, are as follows:

	Shorter Cycle	Longer Cycle
First Cycle length, months	16	20
All subsequent cycles, months	12	18
Design capacity factor, all cycles, %	70	70
Percent of design capacity factor achieved, %	100	100

Parameter 3

Schedule of target burnups. Two schedules were used, the first was applied under the assumption that no new R&D was to be initiated. The second assumes a vigorous extension of the current R&D program.

These schedules, taken from the columns under "Average Utility Selection" in Table 3-3, are as follows:

		Target Burnups, MWD/KgU,(a)					
		1. Without New R&D		2. With New R&D		3. Assuming No Change	
	Date	BWR	PWR	BWR	PWR	BWR	PWR
before	1/1/1980	28.5	33	28.5	33	28.5	33
	1/1/1985	31	39	31	39	28.5	33
	1/1/1990	35	40	38	45	28.5	33
	1/1/1995	38	45	40	50	28.5	33
after	1/1/2000	38	50	43	55	28.5	33

(a) Target burnups at intermediate times are found by linear interpolation.

Type of Reactor	PWR
Reactor Size, Mw(E) net	1067.994
R and D Assumption	R & D Continues

Batch Size a Multiple of

Cycle Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Design Cycle Length, Months	20.00	18.00	17.50	17.89	17.77	17.28	17.57	17.56	17.47	18.04	17.64	17.73	17.47	17.29	17.78	18.53	17.85	18.01	18
Design Capacity Factor	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70
Design Full-Power-Days	426.13	383.51	372.75	381.24	378.65	368.24	374.32	374.10	372.31	384.36	375.80	377.80	372.30	368.35	378.85	394.81	380.25	383.71	383.51
Percent of Design FPD's Achieved	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
Actual Cycle Burnup, Mwd/kgU	17.79	16.01	15.56	15.92	15.81	15.37	15.63	15.62	15.54	16.05	15.69	15.77	15.54	15.38	15.82	16.48	15.87	16.02	16.01
BOC, Year	1980.00	1981.67	1983.17	1984.62	1986.12	1987.60	1989.04	1990.50	1991.96	1993.42	1994.92	1996.39	1997.87	1999.33	2000.77	2002.25	2003.79	2005.28	2006.78
Target Mwd/kgU, Fuel Loaded @ BOC		33.59	35.11	35.11	36.79	38.63	40.66	42.92	45.44	45.44	48.28	48.28	51.50	51.50	51.50	51.50	51.50	51.50	51.5
Average MWD/kgU of Fuel Discharged	17.79	33.80	34.20	34.72	35.81	37.25	39.12	41.42	43.34	45.50	46.55	47.51	48.34	49.04	50.15	51.04	51.50	51.50	51.5
Number of FA's Loaded	193	92	88	88	84	80	76	72	68	68	64	64	60	60	60	60	60	60	60
Number of FA's of Type L		84	72	72	60	48	36	24	12	12	64	64	48	48	48	48	48	48	48
Number of FA's of Type H		8	16	16	24	32	40	48	56	56	0	0	12	12	12	12	12	12	12

Number of Fuel Assemblies Loaded

		Enrich.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Number of FA's	Batch 1	1.89	92																	
	Batch 2	3.33	92	92	4															
	Batch 3	4.12	9	9	9															
	Batch 4	3.21		84	84	9														
	Batch 5	4.25		8	8	8														
	Batch 6	3.21			72	72	5													
	Batch 7	4.25			16	16	16													
	Batch 8	3.21				72	72	13												
	Batch 9	4.25				16	16	16												
	Batch 10	3.20					60	60	13											
	Batch 11	4.24					24	24	24											
	Batch 12	3.20						48	48	13										
	Batch 13	4.24						32	32	32										
	Batch 14	3.19							36	36	13									
	Batch 15	4.23							40	40	40									
	Batch 16	3.18								24	24	9								
	Batch 17	4.22								48	48	48								
	Batch 18	3.18									12	12	5							
	Batch 19	4.22									56	56	56							
	Batch 20	3.18										12	12	9						
	Batch 21	4.22										56	56	56	5					
	Batch 22	4.23											64	64	64	9				
	Batch 23	4.23												64	64	64	13			
	Batch 24	4.20													48	48	48	1		
	Batch 25	5.24													12	12	12	12		
	Batch 26	4.20														48	48	48	1	
	Batch 27	5.24														12	12	12	12	
	Batch 28	4.20															48	48	48	1
	Batch 29	5.24															12	12	12	12
	Batch 30	4.20																48	48	48
	Batch 31	5.24																12	12	12
	Batch 32	4.20																	48	48
	Batch 33	5.24																	12	12
	Batch 34	4.20																		48
	Batch 35	5.24																		12
	Equilibrium Batch A	4.20																		
	Equilibrium Batch B	5.24																		

TABLE 4-3a

Fuel Management, 1980 Plant Startup
18 Month Cycle, PWR, Further R&D Assumed

Type of Reactor	PWR		Batch Size a Multiple of
Reactor Size, Mw(E) net	1067.994		
R and D Assumption	No Further DOE R & D		

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Cycle Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Design Cycle Length, Months	20.00	18.00	17.50	17.89	17.77	17.28	18.09	18.21	17.51	17.91	17.82	17.21	18.13	17.66	17.69	18.34	17.90	17.97	18
Design Capacity Factor	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70
Design Full-Power-Days	426.13	383.51	372.75	381.24	378.65	368.24	385.52	388.01	373.08	381.61	379.60	366.70	386.37	376.21	376.82	390.82	381.29	382.95	383.51
Percent of Design FPD's Achieved	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
Actual Cycle Burnup, Mwd/kgU	17.79	16.01	15.56	15.92	15.81	15.37	16.09	16.20	15.58	15.93	15.85	15.31	16.13	15.71	15.73	16.32	15.92	15.99	16.01
BOC, Year	1980.00	1981.67	1983.17	1984.62	1986.12	1987.60	1989.04	1990.54	1992.06	1993.52	1995.01	1996.50	1997.93	1999.44	2000.92	2002.39	2003.92	2005.41	2006.91
Target Mwd/kgU, Fuel Loaded @ BOC		33.59	35.11	35.11	36.79	38.63	38.63	38.63	40.66	40.66	42.92	45.44	45.44	48.28	48.28	48.28	48.28	48.28	48.28
Average MWD/kgU of Fuel Discharged	17.79	33.00	34.20	34.72	35.81	36.95	37.99	38.97	39.61	40.73	42.09	43.57	45.55	46.43	47.57	48.00	48.21	48.28	48.28
Number of FA's Loaded	193	92	88	88	84	80	80	80	76	76	72	68	68	64	64	64	64	64	64
Number of FA's of Type L		84	72	72	60	48	48	48	36	36	24	12	12	64	64	64	64	64	64
Number of FA's of Type H		8	16	16	24	32	32	32	40	40	48	56	56	0	0	0	0	0	0

Number of Fuel Assemblies Loaded

		Enrich.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Number of FA's	Batch 1	1.89	92																		
	Batch 2	3.33	92	92	4																
	Batch 3	4.12	9	9	9																
	Batch 4	3.21		84	84	9															
	Batch 5	4.25		8	8	8															
	Batch 6	3.21			72	72	5														
	Batch 7	4.25			16	16	16														
	Batch 8	3.21				72	72	13													
	Batch 9	4.25				16	16	16													
	Batch 10	3.20					60	60	9												
	Batch 11	4.24					24	24	24												
	Batch 12	3.20						48	48	1											
	Batch 13	4.24						32	32	32											
	Batch 14	3.20							48	48	5										
	Batch 15	4.24							32	32	32										
	Batch 16	3.20								48	48	9									
	Batch 17	4.24								32	32	32									
	Batch 18	3.19									36	36	5								
	Batch 19	4.23									40	40	40								
	Batch 20	3.19										36	36	13							
	Batch 21	4.23										40	40	40							
	Batch 22	3.18											24	24	9						
	Batch 23	4.22											48	48	48						
	Batch 24	3.18												12	12	5					
	Batch 25	4.22												56	56	56					
	Batch 26	3.18													12	12	9				
	Batch 27	4.22													56	56	56	1			
	Batch 28	4.23														64	64	64	1		
	Batch 29	4.23															64	64	64	1	
	Batch 30	4.23																64	64	64	
	Batch 31	4.23																	64	64	
	Batch 32	4.23																		64	
	Equilibrium Batch A	4.23																			
	Equilibrium Batch B	5.27																			

TABLE 4-3b

Fuel Management, 1980 Plant Startup
18 Month Cycle, PWR, No Further R&D Assumed

Type of Reactor	BWR
Reactor Size, Mw(E) net	1068.096
R and D Assumption	R & D Continues

Batch Size a Multiple of

Cycle Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Design Cycle Length, Months	20.00	18.00	17.97	18.05	17.89	17.30	16.[illegible]	17.09	17.74	17.92	17.96	17.77	17.67	17.60	17.67	17.91	18.04	18.07	18
Design Capacity Factor	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70
Design Full-Power-Days	426.13	383.51	382.81	384.53	381.21	368.68	358.64	364.16	377.99	381.83	382.68	378.51	376.48	375.01	376.52	381.61	384.27	384.94	383.51
Percent of Design FPD's Achieved	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
Actual Cycle Burnup, Mwd/kgU	10.65	9.59	9.57	9.61	9.53	9.22	8.97	9.10	9.45	9.55	9.57	9.46	9.41	9.38	9.41	9.54	9.61	9.62	9.59
BOC, Year	1980.00	1981.67	1983.17	1984.66	1986.17	1987.66	1989.10	1990.50	1991.93	1993.41	1994.90	1996.40	1997.88	1999.35	2000.82	2002.29	2003.78	2005.28	2006.78
Target Mwd/kgU, Fuel Loaded @ BOC		28.31	28.31	28.31	28.76	31.29	34.29	36.39	37.94	38.77	38.77	39.63	40.53	41.47	42.46	42.46	42.46	42.46	42.46
Average MWD/kgU of Fuel Discarged	10.65	20.24	29.30	28.46	28.71	29.10	30.66	32.96	35.13	36.68	37.67	38.44	39.09	39.64	40.40	41.12	41.75	42.46	42.46
Number of FA's Loaded	744	252	252	252	248	228	208	196	188	184	184	180	176	172	168	168	168	168	168
Number of FA's of Type L		12	12	12	248	168	88	40	8	176	176	156	136	116	96	96	96	96	96
Number of FA's of Type H		240	240	240	0	60	120	156	180	8	8	24	40	56	72	72	72	72	72

Number of Fuel Assemblies Loaded

		Enrich.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Number of FA's	Batch 1	1.36	252																		
	Batch 2	2.24	252	252																	
	Batch 3	3.09	240	240	240																
	Batch 4	2.98		12	12																
	Batch 5	2.98		240	240	240															
	Batch 6	2.98			12	12	4														
	Batch 7	2.98			240	240	240	16													
	Batch 8	2.98				12	12	12													
	Batch 9	2.98				240	240	240	60												
	Batch 10	3.00					240	240	240	112											
	Batch 11	3.19						168	168	168	92										
	Batch 12	3.19						60	60	60	60										
	Batch 13	3.38							88	88	88	56									
	Batch 14	3.38							120	120	120	120									
	Batch 15	3.49								40	40	40	32								
	Batch 16	3.49								156	156	156	156	8							
	Batch 17	3.56									8	8	8	8							
	Batch 18	3.56									180	180	180	180	28						
	Batch 19	3.61										176	176	176	176	24					
	Batch 20	3.61										8	8	8	8	8					
	Batch 21	3.61											176	176	176	176	40				
	Batch 22	3.61											8	8	8	8	8				
	Batch 23	3.68												156	156	156	156	36			
	Batch 24	3.68												24	24	24	24	24			
	Batch 25	3.75													136	136	136	136	28		
	Batch 26	3.75													40	40	40	40	40		
	Batch 27	3.82														116	116	116	116	16	
	Batch 28	3.82														56	56	56	56	56	
	Batch 29	3.88															96	96	96	96	
	Batch 30	3.88															72	72	72	72	
	Batch 31	3.88																96	96	96	
	Batch 32	3.88																72	72	72	
	Batch 33	3.88																	96	96	
	Batch 34	3.88																	72	72	
	Batch 35	3.88																		96	
	Batch 36	3.88																		72	
	Equilibrium Batch A	3.88																			
	Equilibrium Batch B	3.88																			

TABLE 4-3c

Fuel Management, 1980 Plant Startup
18 Month Cycle, BWR, Further R&D Assumed

Type of Reactor	BWR								Batch Size a Multiple of		4								
Reactor Size, Mw(E) net	1068.096																		
R and D Assumption	No Further DOE R & D																		
Cycle Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Design Cycle Length, Months	20.00	18.00	17.97	18.05	18.01	17.65	17.10	17.36	17.73	17.78	17.74	17.68	18.07	18.03	18.06	17.95	18.03	18.02	18
Design Capacity Factor	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70
Design Full-Power-Days	426.13	383.51	382.81	384.53	383.62	376.01	364.32	369.89	377.85	378.89	377.98	376.66	385.05	384.08	384.70	382.55	384.12	383.90	383.51
Percent of Design FPD's Achieved	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
Actual Cycle Burnup, Mwd/kgU	10.65	9.59	9.57	9.61	9.59	9.40	9.11	9.25	9.45	9.47	9.45	9.42	9.63	9.60	9.62	9.56	9.60	9.60	9.59
BOC, Year	1980.00	1981.67	1983.17	1984.66	1986.17	1987.67	1989.14	1990.56	1992.01	1993.49	1994.97	1996.45	1997.92	1999.43	2000.93	2002.43	2003.93	2005.43	2006.93
Target Mwd/kgU, Fuel Loaded @ BOC		28.31	28.31	28.31	28.31	30.23	32.42	34.29	34.97	36.39	37.15	37.94	37.94	37.94	37.94	37.94	37.94	37.94	37.94
Average MWD/kgU of Fuel Discarged	10.65	28.24	29.30	28.31	28.77	28.78	29.76	31.52	33.17	34.62	35.84	36.78	37.36	37.69	37.86	38.00	37.98	37.94	37.94
Number of FA's Loaded	744	252	252	252	252	236	220	208	204	196	192	188	188	188	188	188	188	188	188
Number of FA's of Type L		12	12	12	12	200	136	88	72	40	24	8	8	8	8	8	8	8	8
Number of FA's of Type H		240	240	240	240	36	84	120	132	156	168	180	180	180	180	180	180	180	180

Number of Fuel Assemblies Loaded

Number of FA's	Batch	Enrich.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
	Batch 1	1.36	252																		
	Batch 2	2.24	252	252																	
	Batch 3	3.09	240	240	240																
	Batch 4	2.98		12	12																
	Batch 5	2.98		240	240	240															
	Batch 6	2.98			12	12															
	Batch 7	2.98			240	240	240	4													
	Batch 8	2.98				12	12	12													
	Batch 9	2.98				240	240	240	36												
	Batch 10	2.98					12	12	12												
	Batch 11	2.98					240	240	240	88											
	Batch 12	3.11						200	200	200	76										
	Batch 13	3.11						36	36	36	36										
	Batch 14	3.26							136	136	136	52									
	Batch 15	3.26							84	84	84	84									
	Batch 16	3.38								88	88	88	32								
	Batch 17	3.38								120	120	120	120								
	Batch 18	3.41									72	72	72	36							
	Batch 19	3.41									132	132	132	132							
	Batch 20	3.49										40	40	40	20						
	Batch 21	3.49										156	156	156	156						
	Batch 22	3.52											24	24	24	12					
	Batch 23	3.52											168	168	168	168					
	Batch 24	3.56												8	8	8					
	Batch 25	3.56												180	180	180	180				
	Batch 26	3.56													8	8	8				
	Batch 27	3.56													180	180	180	180			
	Batch 28	3.56														8	8	8			
	Batch 29	3.56														180	180	180	180		
	Batch 30	3.56															8	8	8		
	Batch 31	3.56															180	180	180	180	
	Batch 32	3.56																8	8	8	
	Batch 33	3.56																180	180	180	
	Batch 34	3.56																	8	8	
	Batch 35	3.56																	180	180	
	Batch 36	3.56																		8	
	Batch 37	3.56																		180	
	Equilibrium Batch A	3.56																			
	Equilibrium Batch B	3.56																			

TABLE 4-3d

Fuel Management, 1980 Plant Startup
18 Month Cycle, BWR, No Further R&D Assumed

Type of Reactor	PWR					Batch Size a Multiple of													
Reactor Size, MW(E) net	1067.994																		
R and D Assumption	R & D Continues																		
Cycle Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Design Cycle Length, Months	16.00	12.00	11.41	11.12	11.91	11.75	11.96	12.33	11.18	11.45	11.73	12.08	12.46	11.80	11.92	12.01	12.06	12.03	12
Design Capacity Factor	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70
Design Full-Power-Days	340.90	255.68	243.15	236.94	253.73	250.29	254.76	262.72	238.21	244.00	249.87	257.40	265.55	251.46	254.01	255.90	256.85	256.41	255.68
Percent of Design FPD's Achieved	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
Actual Cycle Burnup, Mwd/kgU	14.23	10.67	10.15	9.89	10.59	10.45	10.64	10.97	9.94	10.19	10.43	10.75	11.09	10.50	10.60	10.68	10.72	10.70	10.67
BOC, Year	1990.00	1991.33	1992.33	1993.28	1994.21	1995.20	1996.18	1997.18	1998.21	1999.14	2000.09	2001.07	2002.08	2003.12	2004.10	2005.09	2006.09	2007.10	2008.1
Target Mwd/kgU, Fuel Loaded @ BOC		42.92	42.92	46.82	46.82	46.82	46.82	46.82	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.5
Average MWD/kgU of Fuel Discharged	14.23	24.91	35.06	44.95	44.22	44.24	45.49	46.85	47.56	48.26	49.24	50.36	50.65	51.16	51.54	51.74	51.65	51.50	51.5
Number of FA's Loaded	193	48	48	44	44	44	44	44	40	40	40	40	40	40	40	40	40	40	40
Number of FA's of Type L		48	48	28	28	28	28	28	8	8	8	8	8	8	8	8	8	8	8
Number of FA's of Type H		0	0	16	16	16	16	16	32	32	32	32	32	32	32	32	32	32	32

Number of Fuel Assemblies Loaded

		Enrich.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Number of FA's	Batch 1	1.31	48																	
	Batch 2	2.10	48	48																
	Batch 3	2.88	48	48	48	4														
	Batch 4	3.66	48	48	48	48	8													
	Batch 5	4.06	1	1	1	1	1													
	Batch 6	3.58		48	48	48	48	13												
	Batch 7	3.58			48	48	48	48	17											
	Batch 8	3.55				28	28	28	28	1										
	Batch 9	4.25				16	16	16	16	16										
	Batch 10	3.55					28	28	28	28	5									
	Batch 11	4.25					16	16	16	16	16									
	Batch 12	3.55						28	28	28	28	9								
	Batch 13	4.25						16	16	16	16	16								
	Batch 14	3.55							28	28	28	28	13							
	Batch 15	4.25							16	16	16	16	16							
	Batch 16	3.55								28	28	28	28	17						
	Batch 17	4.25								16	16	16	16	16						
	Batch 18	3.56									8	8	8	8	1					
	Batch 19	4.25									32	32	32	32	32					
	Batch 20	3.56										8	8	8	8	1				
	Batch 21	4.25										32	32	32	32	32				
	Batch 22	3.56											8	8	8	8	1			
	Batch 23	4.25											32	32	32	32	32			
	Batch 24	3.56												8	8	8	8	1		
	Batch 25	4.25												32	32	32	32	32		
	Batch 26	3.56													8	8	8	8	1	
	Batch 27	4.25													32	32	32	32	32	
	Batch 28	3.56														8	8	8	8	1
	Batch 29	4.25														32	32	32	32	32
	Batch 30	3.56															8	8	8	8
	Batch 31	4.25															32	32	32	32
	Batch 32	3.56																8	8	8
	Batch 33	4.25																32	32	32
	Batch 34	3.56																	8	8
	Batch 35	4.25																	32	32
	Batch 36	3.56																		8
	Batch 37	4.25																		32
	Equilibrium Batch A	3.56																		
	Equilibrium Batch B	4.25																		

TABLE 4-3e

Fuel Management, 1990 Plant Startup
12 Month Cycle, PWR, Further R&D Assumed

Type of Reactor	PWR	Batch Size a Multiple of	4
Reactor Size, Mw(E) net	1067.994		
R and D Assumption	R & D Continues		

Cycle Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Design Cycle Length, Months	16.00	12.00	11.25	11.27	12.08	12.67	11.85	11.84	11.97	12.00	12.06	11.96	11.99	12.01	12.02	12.01	12.00	12.01	12
Design Capacity Factor	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70
Design Full-Power-Days	340.90	255.68	239.72	240.10	257.45	269.91	252.38	252.35	255.02	257.44	256.93	254.91	255.45	255.99	256.09	255.83	255.68	255.82	255.68
Percent of Design FPD's Achieved	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
Actual Cycle Burnup, Mwd/kgU	14.23	10.67	10.01	10.02	10.75	11.27	10.54	10.53	10.65	10.75	10.73	10.64	10.66	10.69	10.69	10.68	10.67	10.68	10.67
BOC, Year	2000.00	2001.33	2002.33	2003.27	2004.21	2005.22	2006.27	2007.26	2008.25	2009.24	2010.25	2011.26	2012.25	2013.25	2014.25	2015.25	2016.26	2017.26	2018.26
Target Mwd/kgU, Fuel Loaded @ BOC		51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.50	51.5
Average MWD/kgU of Fuel Discharged	14.23	24.91	34.91	44.94	53.19	50.85	50.83	51.36	51.85	51.76	51.35	51.45	51.56	51.59	51.53	51.50	51.53	51.50	51.5
Number of FA's Loaded	193	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Number of FA's of Type L		8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Number of FA's of Type H		32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32

Number of Fuel Assemblies Loaded

		Enrich.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Equil.
Number of FA's	Batch 1	1.16	40																		
	Batch 2	1.91	40	40																	
	Batch 3	2.67	40	40	40																
	Batch 4	3.42	40	40	40	40															
	Batch 5	4.11	33	33	33	33	33														
	Batch 6	3.56		8	8	8	8	1													
	Batch 7	4.25		32	32	32	32	32													
	Batch 8	3.56			8	8	8	8	1												
	Batch 9	4.25			32	32	32	32	32												
	Batch 10	3.56				8	8	8	8	1											
	Batch 11	4.25				32	32	32	32	32											
	Batch 12	3.56					8	8	8	8	1										
	Batch 13	4.25					32	32	32	32	32										
	Batch 14	3.56						8	8	8	8	1									
	Batch 15	4.25						32	32	32	32	32									
	Batch 16	3.56							8	8	8	8	1								
	Batch 17	4.25							32	32	32	32	32								
	Batch 18	3.56								8	8	8	8	1							
	Batch 19	4.25								32	32	32	32	32							
	Batch 20	3.56									8	8	8	8	1						
	Batch 21	4.25									32	32	32	32	32						
	Batch 22	3.56										8	8	8	8	1					
	Batch 23	4.25										32	32	32	32	32					
	Batch 24	3.56											8	8	8	8	1				
	Batch 25	4.25											32	32	32	32	32				
	Batch 26	3.56												8	8	8	8	1			
	Batch 27	4.25												32	32	32	32	32			
	Batch 28	3.56													8	8	8	8	1		
	Batch 29	4.25													32	32	32	32	32		
	Batch 30	3.56														8	8	8	8	1	
	Batch 31	4.25														32	32	32	32	32	
	Batch 32	3.56															8	8	8	8	
	Batch 33	4.25															32	32	32	32	
	Batch 34	3.56																8	8	8	
	Batch 35	4.25																32	32	32	
	Batch 36	3.56																	8	8	
	Batch 37	4.25																	32	32	
	Batch 38	3.56																		8	
	Batch 39	4.25																		32	
	Equilibrium Batch A	3.56																			
	Equilibrium Batch B	4.25																			

TABLE 4-3f

Fuel Management, 2000 Plant Startup
12 Month Cycle, PWR, Further R&D Assumed

TABLE 4-4

Nuclear Growth Projections (2)
(gigawatts)

Year	No New Orders	Middle
1985	81	85
1986	88	94
1987	98	104
1988	104	105
1989	106	107
1990	107	111
1991	108	113
1992	108	117
1993	109	119
1994	109	119
1995	109	119
1996	109	122
1997	109	123
1998	109	123
1999	109	123
2000	108	123
2001	108	127
2002	108	132
2003	108	138
2004	108	143
2005	108	148
2006	108	152
2007	108	155
2008	108	159
2009	108	162
2010	106	166
2011	108	171
2012	99	175
2013	91	180
2014	74	184
2015	68	189
2016	60	194
2017	56	198
2018	53	203
2019	49	207
2020	49	212

TABLE 4-5

COMPARISON OF DIFFERENTIAL FUEL CYCLE COST (FCC) THROUGH 2020

(Millions of 1985$, Discounted To 1/85)

	No New Orders Nuclear Capacity Case			
	FCC With Mill/kwh Fee	FCC With Credit Proportional To Volume	FCC With Credit Proportional to Volume And Energy	FCC With No Disposal Charge
Net Benefit of Supporting Extended Burnup Research and Development	490	840	730	490

	Middle Growth Nuclear Capacity Case			
	FCC With Mill/kwh Fee	FCC With Credit Proportional To Volume	FCC With Credit Proportional to Volume And Energy	FCC With No Disposal Charge
Net Benefit of Supporting Extended Burnup Research and Development	550	980	840	550

TABLE 4-6

COMPARISON OF BENEFIT-COST RATIO OF EXTENDED BURNUP R&D

	Benefit-Cost Ratio With Mill/kwh Disposal Fee	Benefit-Cost Ratio With Credit Proportional to Volume Reduction Due To Extended Burnup*	Benefit-Cost Ratio With Lesser Credit Proportional to Volume Reduction Due to Extended Burnup**	Benefit-Cost Ratio Considering Only Front-End Benefits
No New Orders Nuclear Capacity Case	22	38	33	22
Middle Growth Nuclear Capacity Case	25	44	38	25

* Proportional to $/kgU.

** Proportional to $/kgU + $/MwD.

TABLE 4-7

Projected Research and Development Expenditures for New Extended Burnup Projects.

Year	(millions of dollars) Annual Costs
1987	6
1988	6
1989	3
1990	2
1991	3
1992	3
1993	6
1994	6
Total =	35

Present Worth @ 7.318 %/Year = 22.3 Million Dollars

TABLE 4-8

COMPARISON OF DIFFERENTIAL FUEL CYCLE COST (FCC) THROUGH 2020

(Millions of 1985$, Undiscounted)

	No New Orders Nuclear Capacity Case			
	FCC With Mill/kwh Fee	FCC With Credit Proportional To Volume	FCC With Credit Proportional to Volume And Energy	FCC With No Disposal Charge
Net Benefit of Supporting Extended Burnup Research and Development	1230	2140	1820	1230

	Middle Growth Nuclear Capacity Case			
	FCC With Mill/kwh Fee	FCC With Credit Proportional To Volume	FCC With Credit Proportional to Volume And Energy	FCC With No Disposal Charge
Net Benefit of Supporting Extended Burnup Research and Development	1640	2940	2470	1640

Figure 4-1

Change in PWFRR for Equilibrium Cycle

PWR - 12 Month Cycle

Tax Adjusted Cost of Money = 7.813%/yr

Batch Size a Multiple of 4.

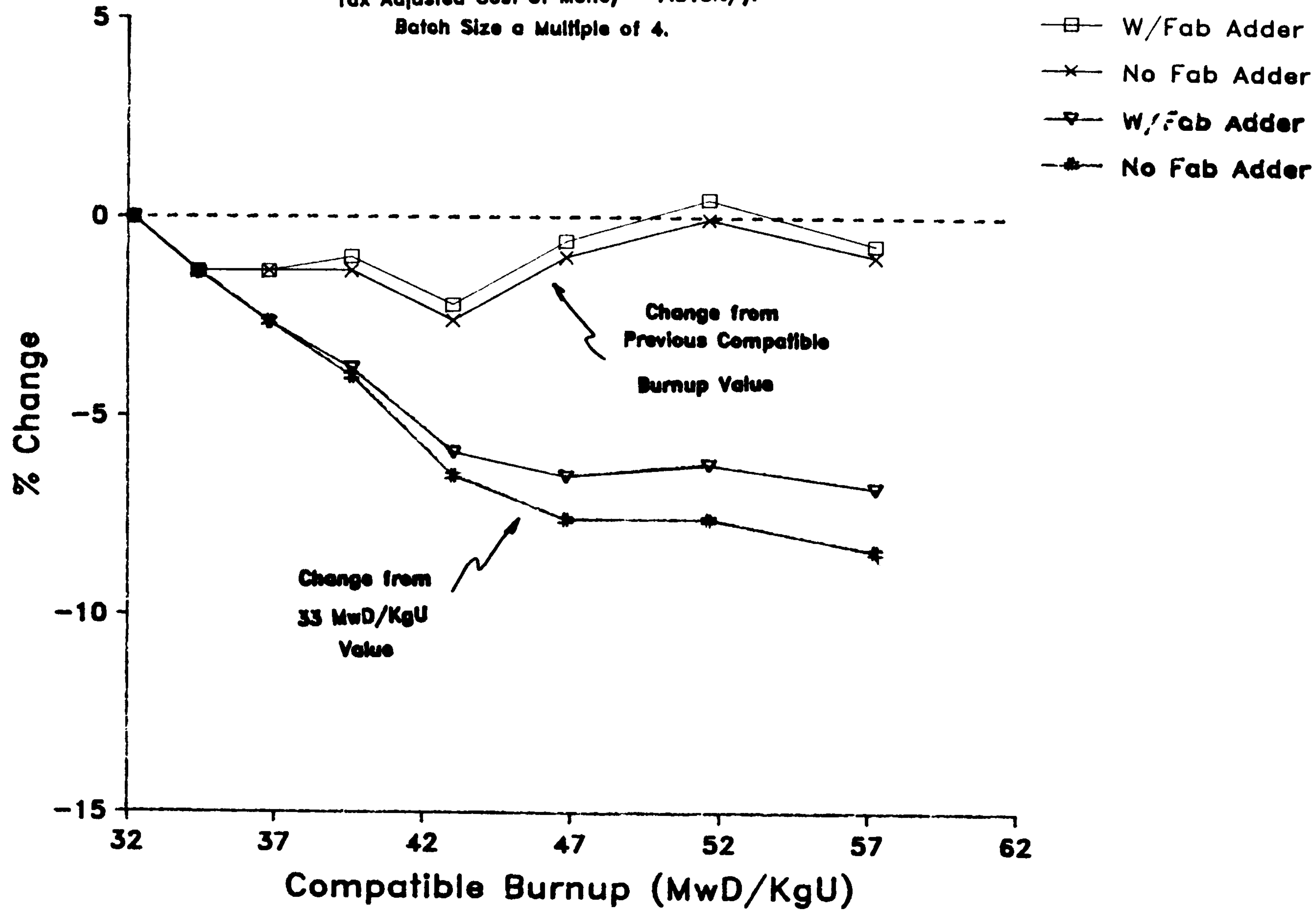


Figure 4-2

Change in PWFRR for Equilibrium Cycle

PWR - 18 Month Cycle

Tax Adjusted Cost of Money = 7.813%/yr

Batch Size a Multiple of 4.

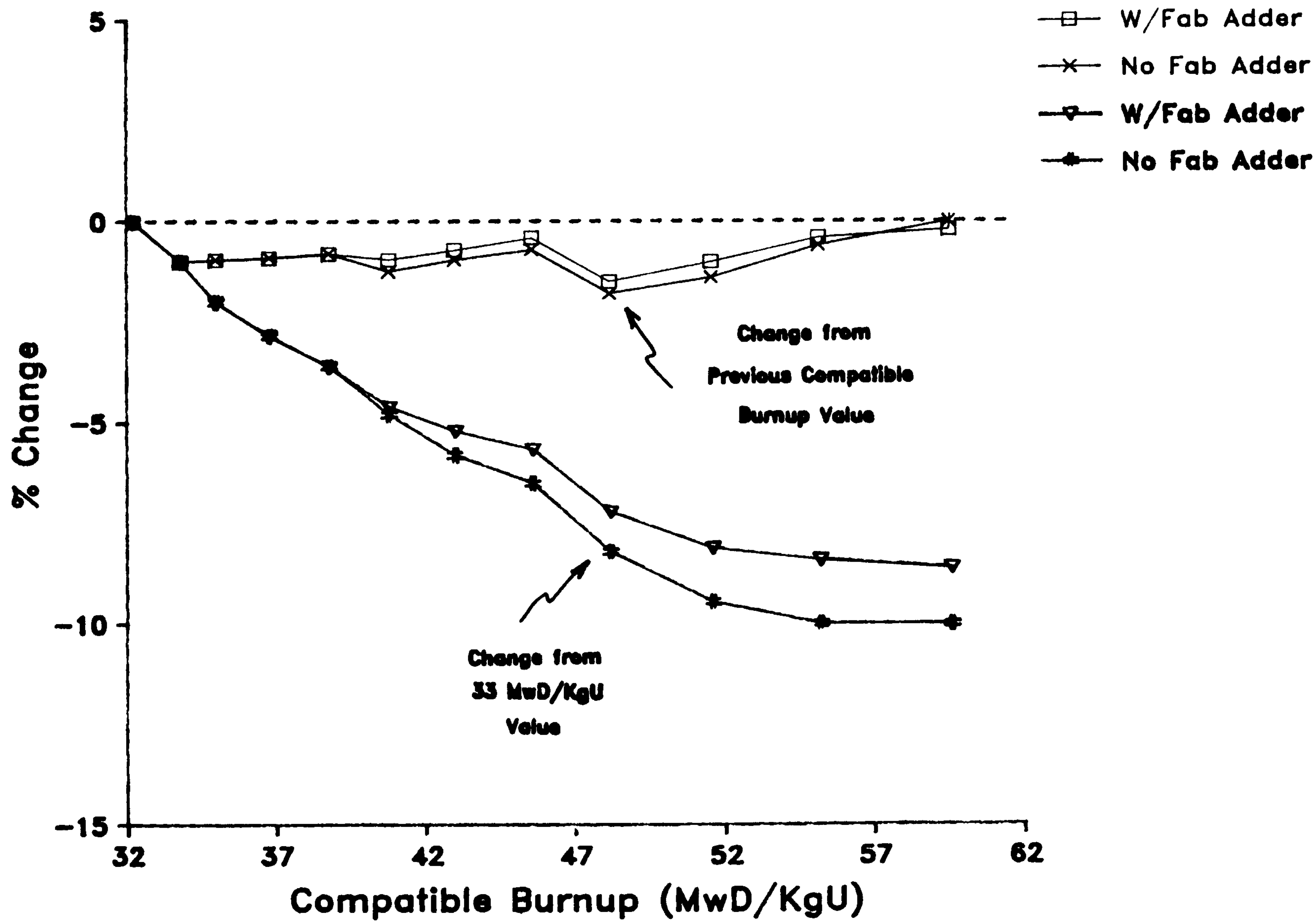


Figure 4-3

Change in PWFRR for Equilibrium Cycle

BWR - 12 Month Cycle

Tax Adjusted Cost of Money = 7.813%/yr

Batch Size a Multiple of 4.

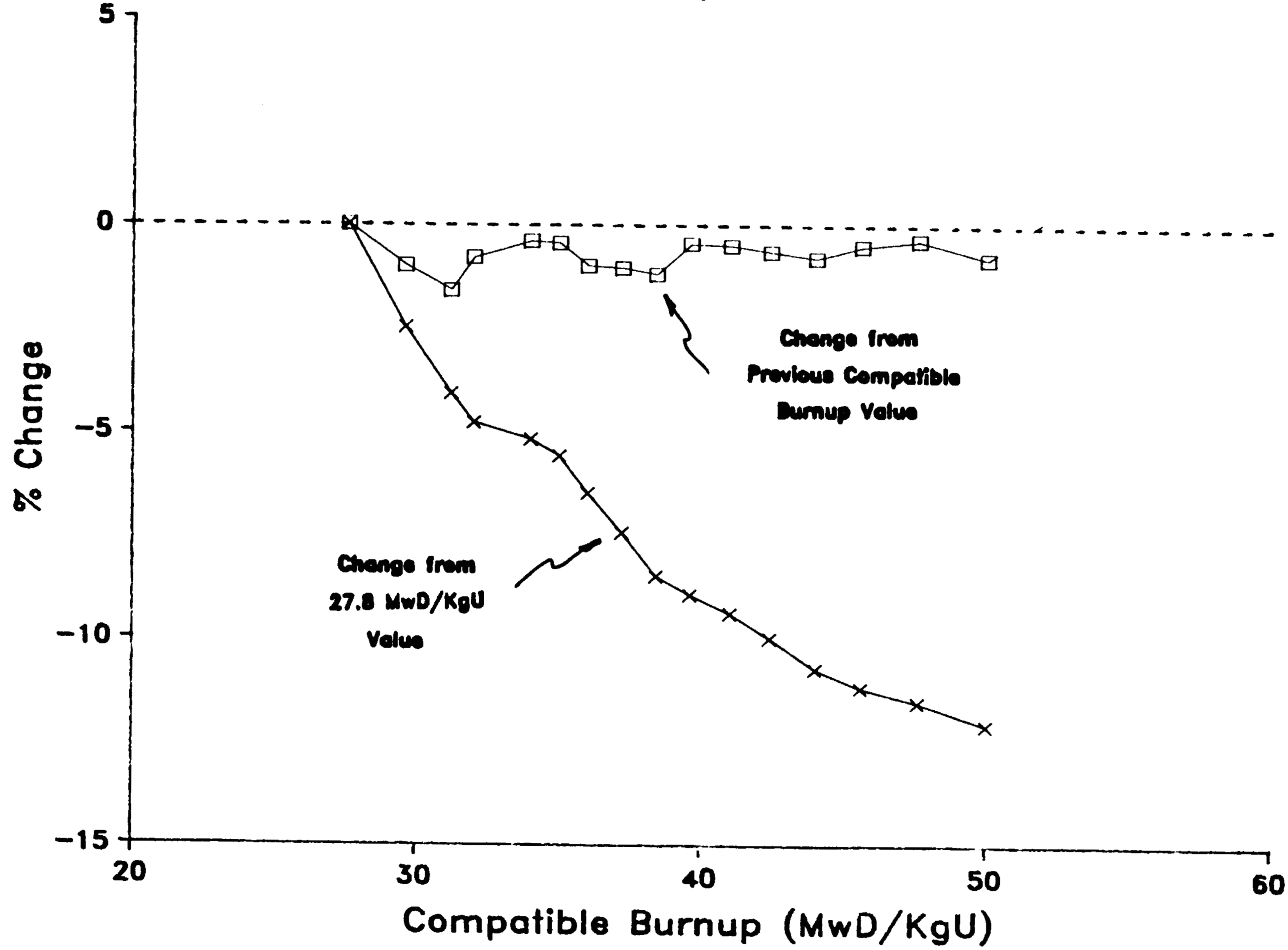


Figure 4-4

Change in PWFRR for Equilibrium Cycle

BWR - 18 Month Cycle

Tax Adjusted Cost of Money = 7.813%/yr

Batch Size a Multiple of 4.

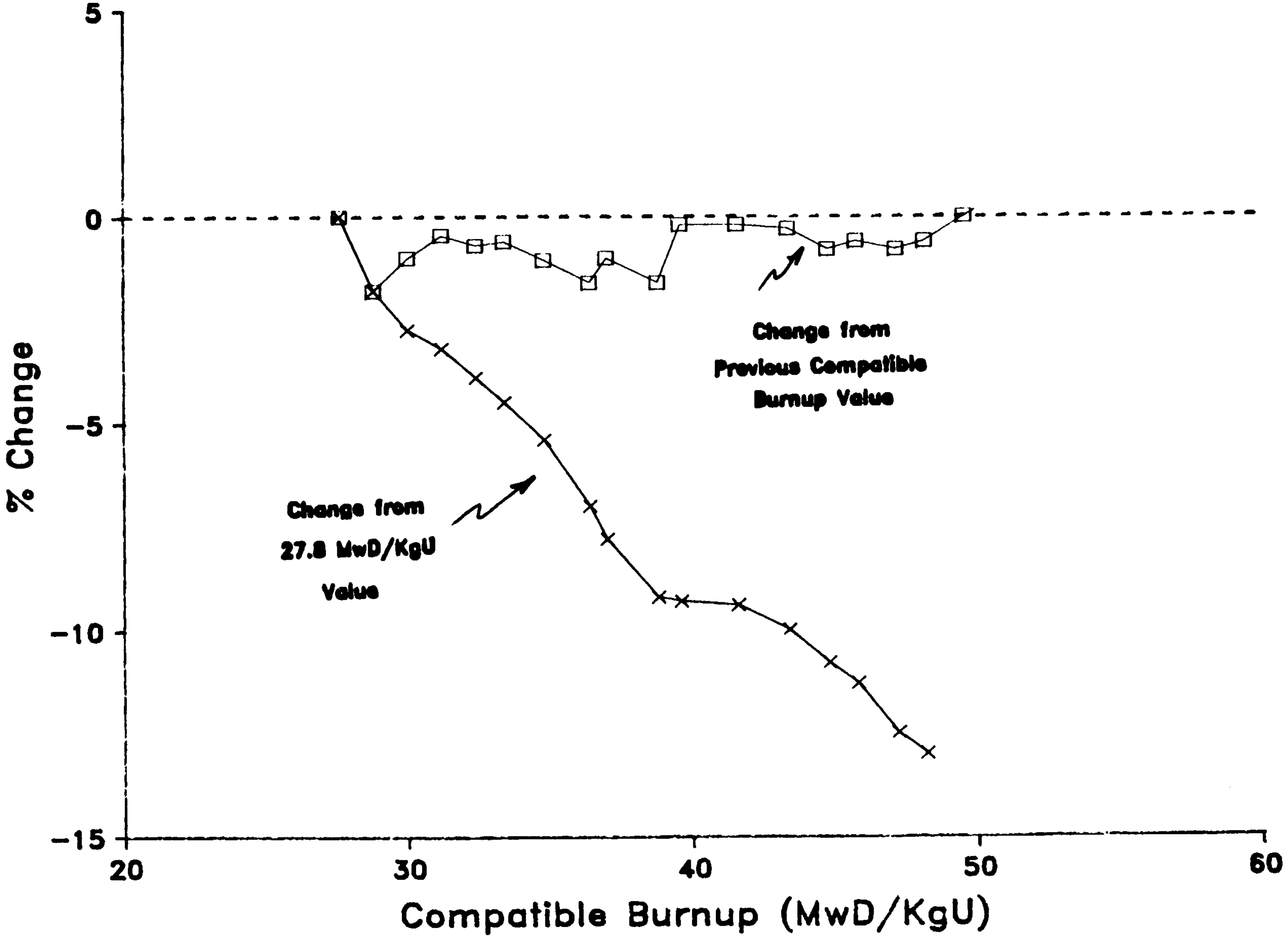


Figure 4–5

Change in PWFRR for Equilibrium Cycle
Comparing the Change in PWFRR with two
Uranium and Conversion Prices

BWR – 18 Month Cycle
Tax Adjusted Cost of Money = 7.813%/yr
Batch Size a Multiple of 4.

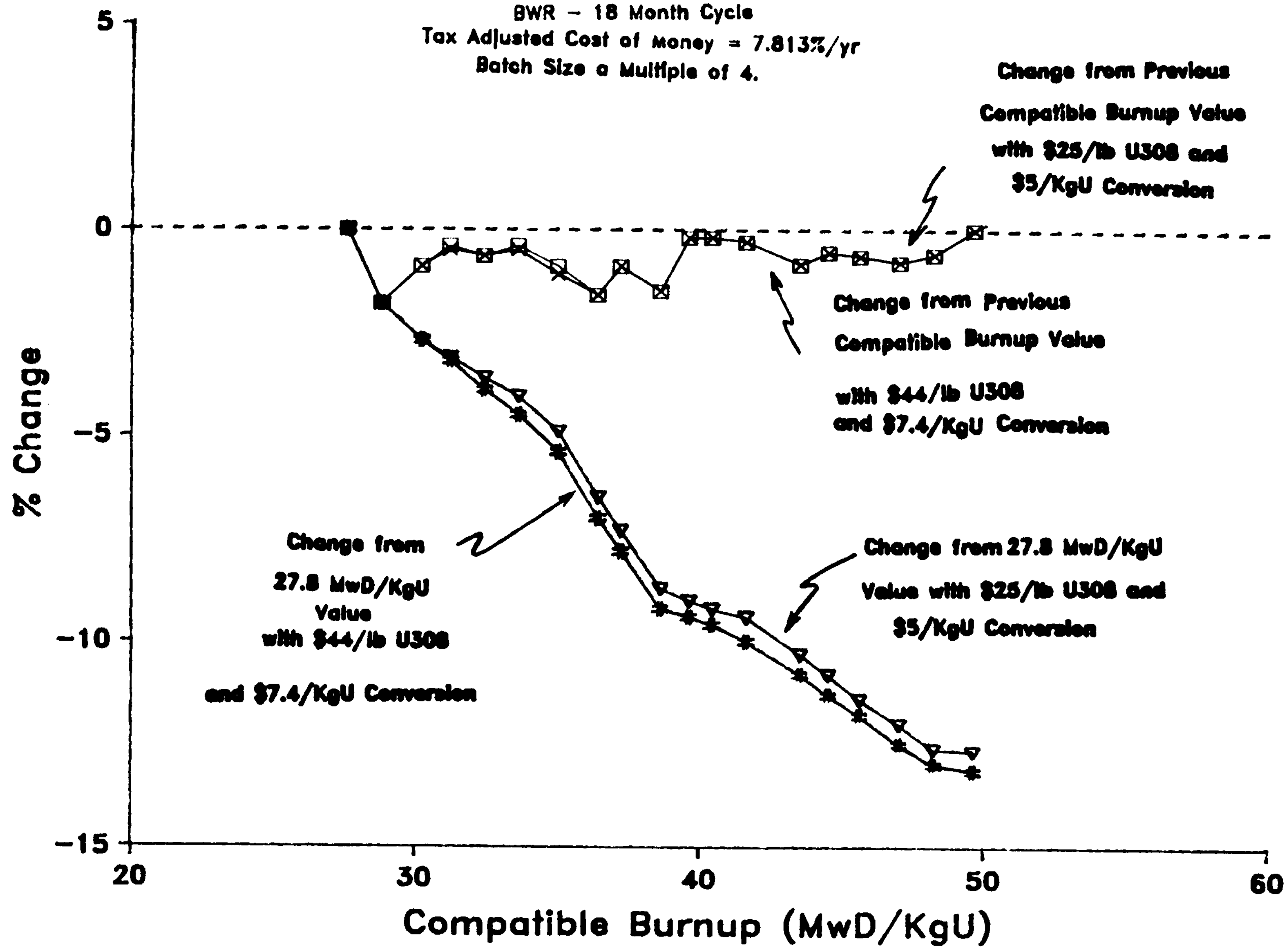


Figure 4-6

Comparison of the Back-end Component Using Different Charge Formulations. All are Relative to the mill/kwh Charge at 33 MwD/KgU

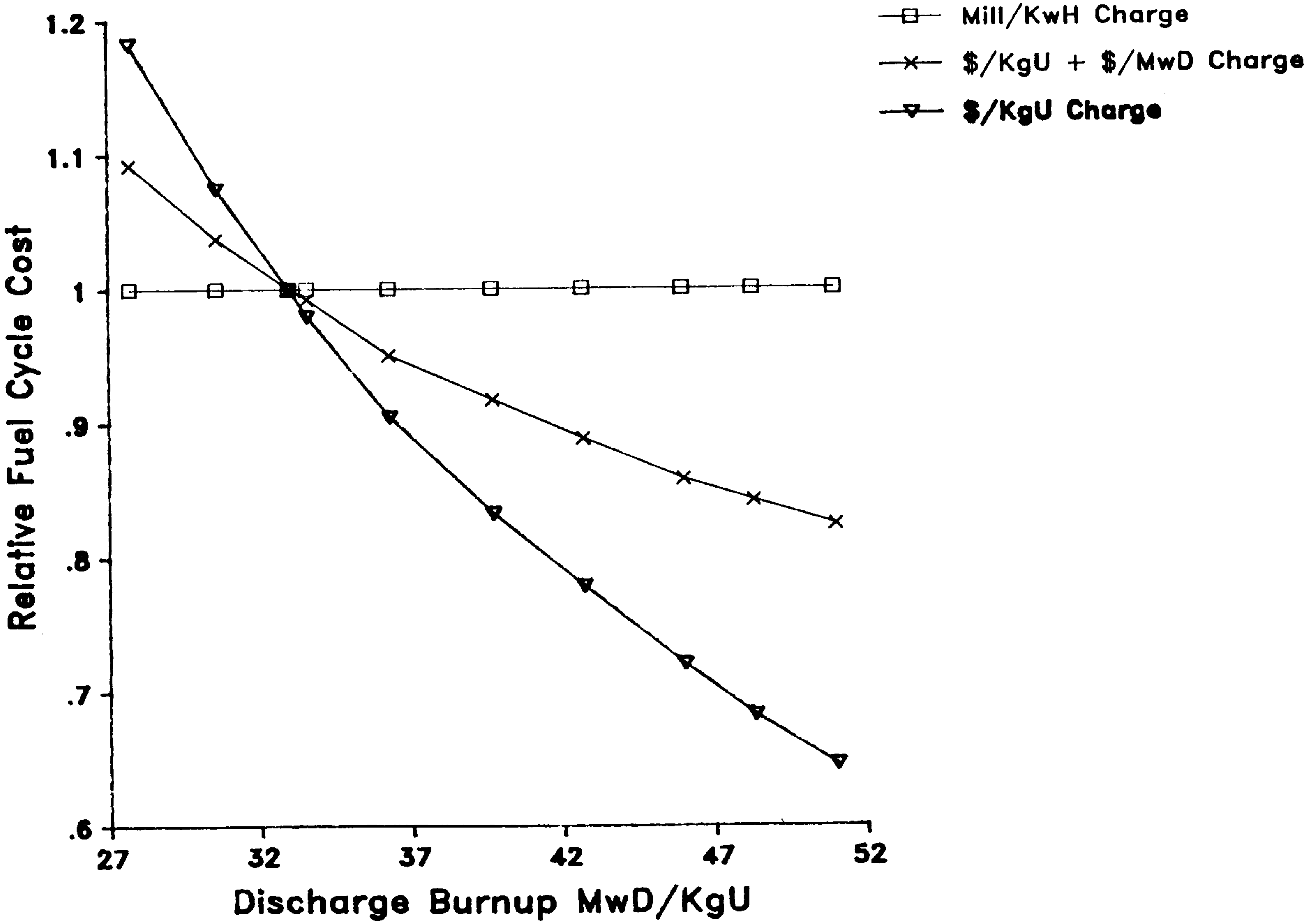


Figure 4–7

Proportion of Long and Short Cycles

Versus Year of Operation

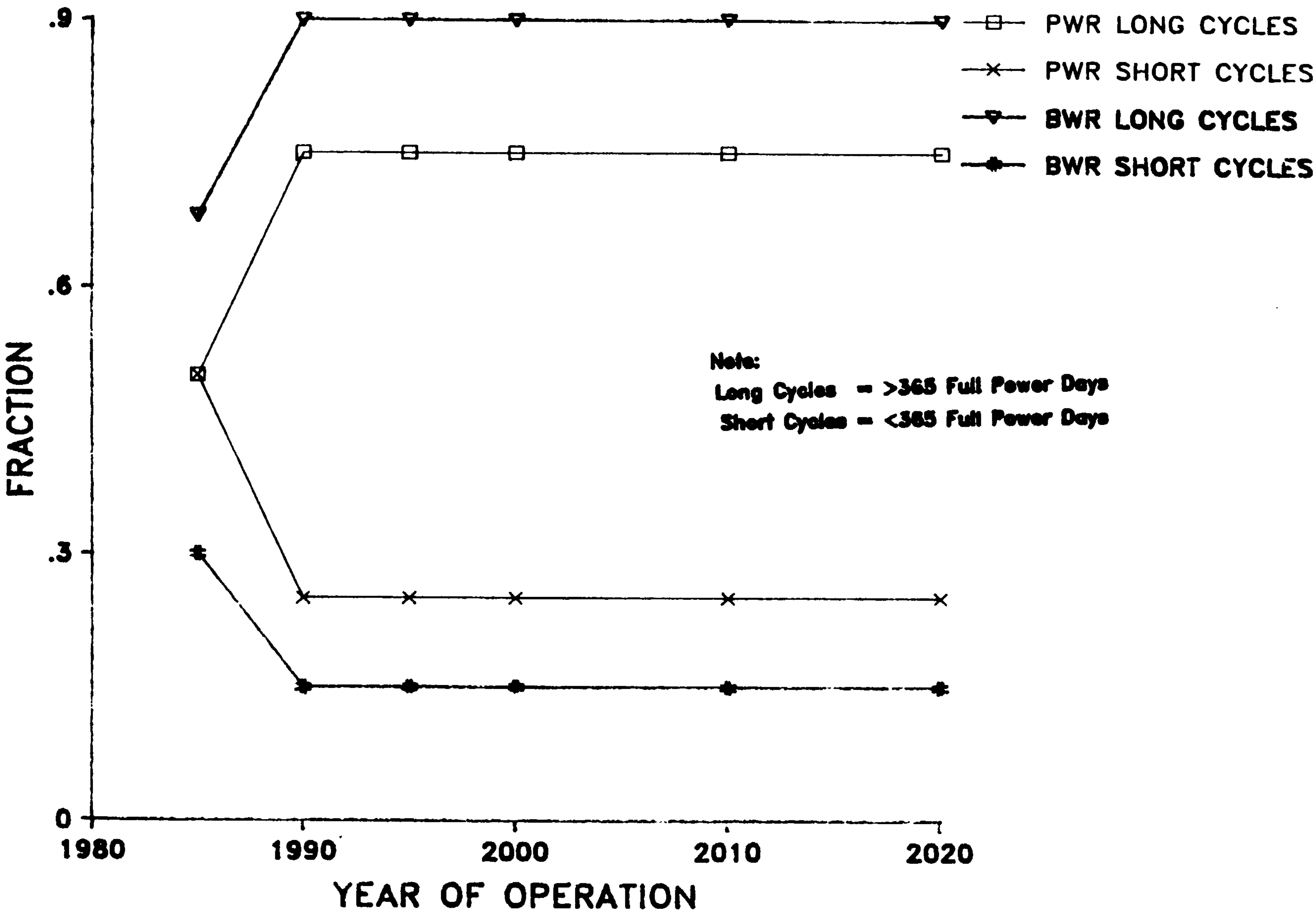
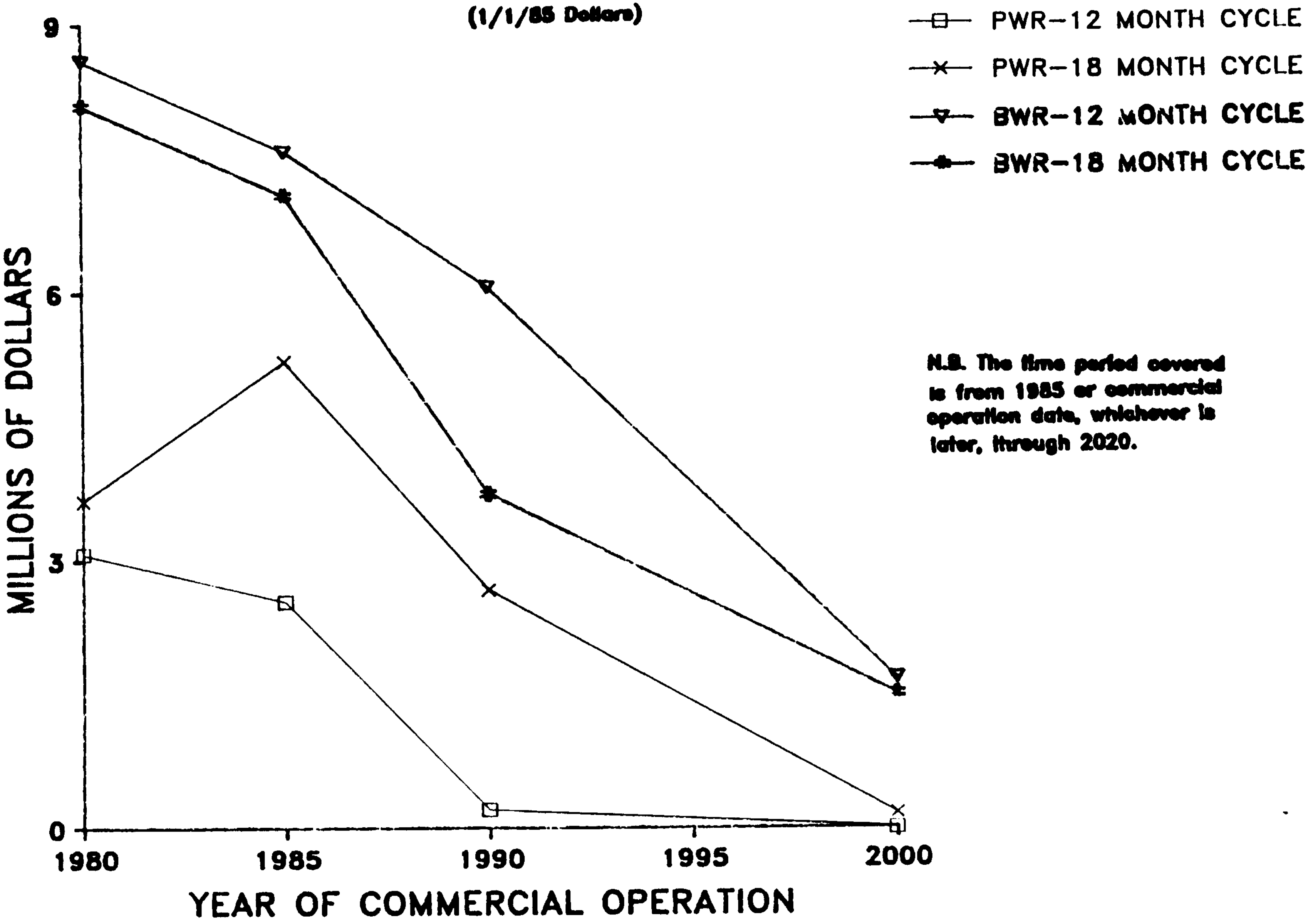


Figure 4-8

Comparison of the differential present worth of future revenue requirements with Mill/KwH Fee for different reactor types and fuel cycles (1/1/85 Dollars)



N.B. The time period covered is from 1985 or commercial operation date, whichever is later, through 2020.

Figure 4-9

Comparison of the differential present worth of future revenue requirements with $/KgU Charge for different reactor types and fuel cycles (1/1/85 Dollars)

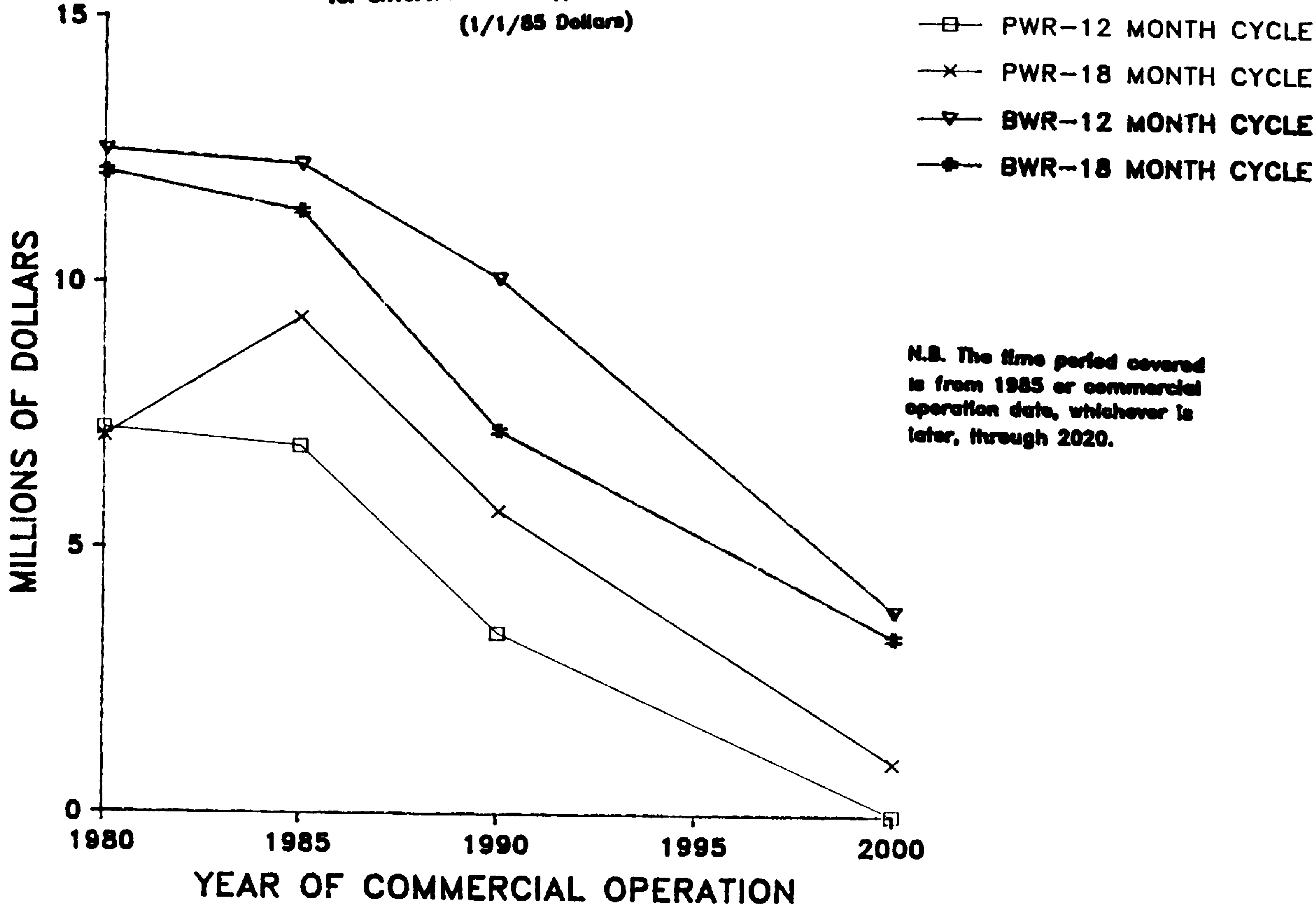
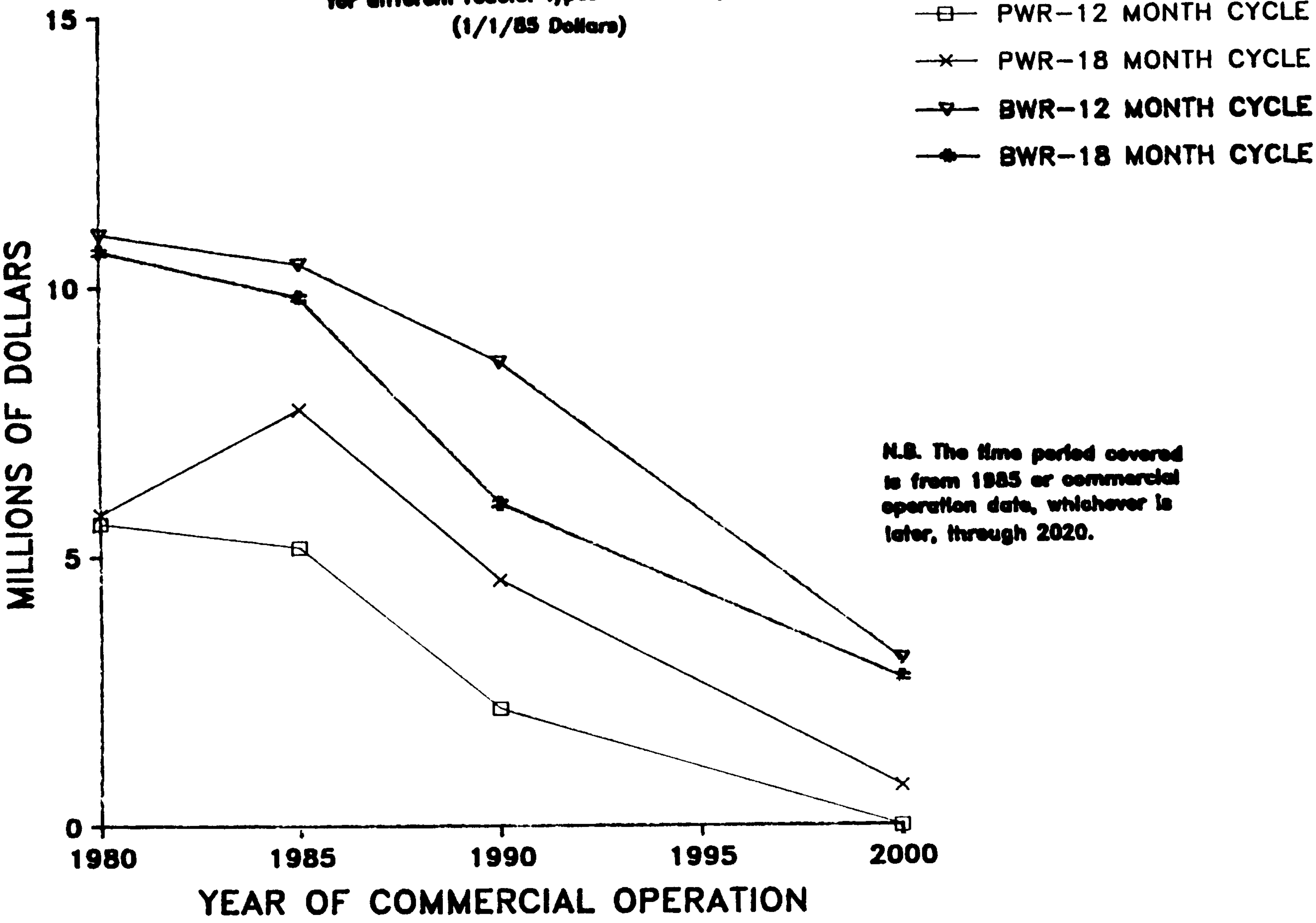


Figure 4-10

Comparison of the differential present worth of future revenue requirements with Mill/KwH + $/MwD (Combined) Charge for different reactor types and fuel cycles (1/1/85 Dollars)



N.B. The time period covered is from 1985 or commercial operation date, whichever is later, through 2020.

5.0 Conclusions

1. Using the fuel cycles and fuel cycle unit commodity costs developed in this study there are present worth fuel cost benefits through additional burnup increases from new R&D support of from 490 million to 980 million dollars over the next thirty five years.

2. The benefit-cost ratios range from 22 to 44: these depend on the application of the alternate backend cost formulations for waste system cost savings assumed for extended burnups.

3. The incremental benefits of achieving higher burnups for the model BWR used in this study are about twice that for PWRs for the front-end component of the cost for the burnup schedules used in this analysis. The back-end components are comparable.

6.0 References

1. Telecon with Dr. Peter Lang, DOE, 2/28/85.

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3. "LWR Fuel-cycle Costs as a Function of Burnup, performed by The S. M. Stoller Corporation, EPRI NP-3788, Electric Power Research Institute, November 1984.

4. "Review of Extended Burnup Research Development, and Implementation in the United States", Peter M. Lang, USDOE, and David M. Franklin, EPRI, IAEA Specialists' Meeting of Improved Utilization of Water Reactor Fuel with Special Emphasis on Extended Burnups and Plutonium Recycling, Mol, Belgium, May 1984.

APPENDIX 1

DEVELOPMENT OF THE DISPOSAL CHARGE FORMULATIONS

The three disposal charge formulations used were developed to illustrate possible credits for the savings in disposal costs associated with higher burnups.

In formulating our disposal charge treatment we started with the current mill/kwh fee.

If one defines:

PW_1 = the present worth of the disposal charges for a reactor fuel cycle based on the mill/kwh fee

PW_2 = the present worth of the disposal charges for a reactor fuel cycle based on a \$/kgU charge

PW_3 = the present worth of the disposal charge based on a combination of PW_1 and PW_2

B_k = cycle burnup (MwD/KgU)

M_o = the initial metric tonnes of uranium in the core at any cycle

d_k = the present worth factor applied to cycle k assuming the cycle produced energy uniformly and it is continuously discounted to 1/1/85

M_k = the initial MtU discharged at end-of-cycle (EOC) k

then at a thermal efficiency of 31.5%

$\$1/Mwh(e) = \$0.315/Mwh(t) = \$.315 \times 24/MwD_t = \$7560/GwD_t$

$$PW_1 = \sum_k 7560 \quad \beta_k M_o d_k$$

$$= 7560 \sum F_k d_k$$

when $F_k = \beta_k M_o$

$$PW_2 = \sum_k (\$/kgU)_o \cdot 1000 \cdot M_k d_k$$

$(\$/kgU)_o$ is chosen such that $PW_1 = PW_2$ for some condition. If this condition is: an LWR, equilibrium in all cycles, then

$$F_k = \beta_k M_o = B_k M_k$$

where B_k = average discharge burnup at (EOC) k

for all cycles, with

$$B_k = B_{eq,o}, \qquad M_k = M_{eq,o}$$

$$M_{eq,o} = \frac{\beta_k M_o}{B_{eq,o}} = \frac{F_k}{B_{eq,o}}$$

where the subscript "o" denotes that the entire disposal charge is based on \$/kgU

$$PW_2 = 1000 \ (\$/kgU)_o \quad \sum_k \frac{F_k d_k}{B_{eq,o}}$$

$$= 1000 \ (\$/kgU)_o \ \cdot \ \sum_k \frac{F_k \ d_k}{B_{eq,o}}$$

$$= 1000 \frac{(\$/kgU)_o}{B_{eq,o}} \cdot \frac{PW_1}{7560}$$

for normalization at an equilibrium discharge exposure this implies that

$$(\$/kgU)_o = 7.56\ B_{eq,o}$$

For

$B_{eq,o} = 36$ $\quad\quad (\$/kgU)_o = 272.16$

$B_{eq,o} = 33$ $\quad\quad (\$/kgU)_o = 249.48$

Defining

$$PW_3 = \sum_k (\$/MWD) \cdot B_k \cdot 1000 \cdot M_k d_k + \sum_k (\$/kgU)_1 \cdot 1000\ M_k d_k$$

where the subscript "1" indicates the $/kgU term is a term in a partial charge

$$PW_3 = 1000 \cdot (\$/MwD) \cdot \sum_k \frac{(B_k\ M_k)}{F_k} F_k d_k + \frac{(\$/kgU)_1}{(\$/kgU)_o} \cdot PW_2$$

in equilibrium $\quad \dfrac{B_k M_k}{F_k} = 1, \quad PW_2 = PW_1$

and if ($/MwD) is to be chosen to make $PW_3 = PW_1$ then

$$PW_1 = 1000 \cdot (\$/MWD) \sum_k F_k d_k + \frac{(\$/kgU)_1}{(\$/kgU)_0} \cdot PW_1$$

$$= \frac{1000 \cdot (\$/MWD)}{7560} PW_1 + \frac{(\$/kgU)_1}{(\$/kgU)_0} PW_1$$

hence

$$\$/MWD = \left(1 - \frac{(\$/kgU)_1}{(\$/kgU)_0}\right) \times 7.56$$

If r = the ratio of the energy component of disposal costs to the volume component

$$r = \frac{1000 (\$/MWD)}{7560} \cdot \frac{(\$/kgU)_0}{(\$/kgU)_1}$$

$$\$/MWD = 7.56r \frac{(\$/kgU)_1}{(\$/kgU)_0} = 7.56 \left(1- \frac{(\$/kgU)_1}{(\$/kgU)_0} \right)$$

$$(\$/kgU)_1 = (\$/kgU)_0 / 1+r = 7.56B_{eq} / 1+r$$

$$\$/MWD = \frac{7.56r}{1+r}$$

Thus for $(\$/kgU)_0 = 250$

and $r = 1.0$

when energy cost represents 50% of the total disposal cost and volume 50% of the costs, then:

$\$/MWD = 3.78$ and $(\$/kgU)_1 = 125$

APPENDIX 2

EFFECT OF BURNUP ON CLAD CHARACTERISTICS

I. The Problem

The purpose of this review is to determine the impact of extended burnup of LWR fuel assemblies on fuel handling after final discharge. A typical PWR assembly is shown in Figure 1 and a typical BWR assembly in Figure 2.

This assessment considers the impact of extended burnup on the Zircaloy structural components of the fuel assembly. Consideration could be given to the effects of extended burnup on the stainless steel components. But the effects of irradiation and corrosion in degrading stainless steel mechanical properties are not considered critical concerning fuel handling after extended burnup.

Information on Zircaloy clad characteristics for extended burnup is available at reactor operating temperatures, but is scarce at temperatures found in spent fuel pools. The characteristics imparted to Zircaloy by irradiation in thermal reactors will affect the mechanical properties by increasing strength and decreasing ductility. Also important is the effect of oxidation by the LWR coolant and hydrogen pickup by the Zircaloy, and the combined effect of these on the Zircaloy properties.

The coolant (water) chemistry can play a major role in oxidation and hydriding at reactor operating temperature, but this is not within the scope of this review.

In evaluating the effect of extended burnup on Zircaloy, in PWRs and BWRs, we must consider the structural elements in the assemblies; empty guide or thimble tubes in PWRs (Fig. 1) and fueled tie rods in BWRs (Fig. 2). In both cases, the grid spacers attached to the guide tubes or tie rods are the structural elements that support the fuel rods. For extended burnup fuel assemblies Zircaloy spacers are expected to be the standard product.

The impact of extended burnup on fuel handling is determined to a large extent by the properties of the Zircaloy in the guide tubes, clad and to a lesser extent the spacers.

This appendix reviews the effect of extended burnup on the Zircaloy guide tubes, clad and spacers and its effect on the in pool and back-end handling. For PWRs the extended burnup fuel designs will increase the exposure time of Zircaloy components from the current level of three years to five or more years. In a BWR the exposure time will increase from the current level of four years to six or more years. In this review we considered an extension of burnup from $\sim$ 33000 MwD/MtU to $\sim$ 45,000 MwD/MtU and higher.

II. Important Characteristics

In handling spent fuel assemblies in the storage pool the temperature of the Zircaloy components is unlikely to greatly exceed 212°F. Technical specification requirements, which must be approved by the NRC, require that the storage pool water not boil.

There is much data for Zircaloy at reactor operating temperature ($\sim$ 570°F for coolant and $\sim$ 650°F for clad in PWRs and $\sim$ 545°F for coolant and $\sim$ 570°F for clad for BWR's). However, little data is available at spent fuel pool temperatures < 212°F (clad slightly higher).

The parameters of importance for assessing the effect of irradiation on spent fuel handling in extended burnup assemblies are:

- the effect of radiation on mechanical properties of Zircaloy at spent fuel temperatures;

- Zircaloy corrosion oxidation and hydriding;

- Spacer relaxation or deterioration (as affected by corrosion and/or irradiation effect on its mechanical properties).

Spacer relaxation is in fact more related to fuel rod behavior in service. Spacer deterioration (cracking, oxidation, hydriding, irradiation embrittlement) could adversely affect fuel assembly handling after extended burnup.

This appendix will present data obtained during post irradiation examination of PWR guide tubes, BWR fueled tie rods and Zircaloy spacers for both types of LWRs.

III. Data Available

Post irradiation examination has been performed on Zion PWR components after three and five cycles[1]:

- the five cycles resulted in an assembly average burnup of 54,800 MwD/MtU and a fast fluence of 1.3×10^{22} n/cm^2 (E$\sim$ 1MeV)

- the three cycle examination took place after burnups of approximately 39,00 MwD/MtU and a fast fluence of 7.0×10^{21} (E$\sim$ 1Mev).

The Zircaloy-4 thimble tubes were analyzed after 3 and 5 cycles for oxide film thickness (Table 1), hydrogen concentration in thimble tubes (Table 2), and tensile tests run at room temperature (Table 3).

As shown in Table 1, the oxide film thickness in thimble tubes for 5 cycles went up to 0.43 mils (span 6). For 3 cycles the maximum was 0.39

mils. The hydrogen in the thimble tubes at beginning of life was approximately 10ppm. After 5 cycles it had increased to a maximum of 178ppm; after 3 cycles to a maximum of 63ppm.

In the 178ppm (span #6), a few of the hydride platelets in the metallographic samples examined were oriented radially near the other surface. Despite this, no excessive hydriding or embrittling was found.

The results of tensile tests at room temperature on thimble tube samples are given in Table 3. While the ultimate tensile strength and 0.2% yield strength have increased, the difference between three and five cycles is not great. A saturation effect in Zircaloy is exhibited after approximately 5×10^{19} n/cm^2 (E∽ MeV)[2]. The more critical property is the ductility (elongation) remaining after 3 and 5 cycles. Span 6 of the thimble tubes measured again showed the lowest residual ductility, yet overall the residual ductility is considered adequate for fuel assembly handling (uniform elongation of 1.9 and 3.0%).

Elongation and reduction of area are convenient methods for obtaining information on the total deformation that occurs before failure. These ductility properties allow for some redistribution of stress during fuel assembly handling and permit some overload without catastrophic failure.

The elongation required for these purposes depends on the application and is not normally selected on the basis of design calculations[4]. For the following reasons we can deduce that fuel assemblies can be handled safely after higher burnups (up to ∽55,000 MwD/MtU):

1. The thimble tube uniform and total elongation value are fairly close after three and four cycles (Table 3).
2. They range between 1.9% and 8.0%.
3. The fuel assemblies have been safely handled after three cycles.

The Zircaloy-4 grids of Zion[1] were examined after 3 cycles and no evidence of in-reactor deterioration of any type was seen. After 5 cycles, all visible surfaces of the grids appeared intact with no evidence of cracks, torn straps, broken or distorted springs, or abnormal corrosion. The brazed joint on peripheral straps as well as the visible portion of intersect joints of interior grid straps appeared to be sound and showed no signs of erosion or other deterioration.[1]

After 5 cycles = 55,000 MwD/MtU with a cumulative fluence of $\sim 10.5 \times 10^{21}$ n/cm^2 ($E \sim 1 MeV$), Zircaloy-4 used for thimble tubes demonstrated strength and ductility values, oxide film thickness and hydrogen pickups. These were all in a range indicating adequate strength to permit subsequent fuel handling.

Four bundles operated for more than 8 years in Monticello (BWR)[3] attained average burnups ranging from 42,200 to 45,600 MwD/Mt. All examinations showed the bundles and fuel were in good condition for the high exposures achieved.

The overall average oxide thickness was 1.2 mils and the average hydrogen pickup was 74ppm, with a maximum of 121 ppm. Room temperature tensile tests run on Localized Ductility Arc (LDA) specimens from clad exposed to a fast fluence estimated to be $\sim 7.8 - 8.4 \times 10^{21}$ $n/cm^2 (E>1MeV)$ gave an ultimate tensile strength of 130,000 psi with an elongation of 3.2%. Uniaxial tensile tests in air at 25^oC (77^oF) for the same radiation exposure gave the following results on the Zircaloy -2 clad:

	Sample#1	Sample#2
Ultimate tensile strength	127,700,	133,300 psi
0.2% yield strength	119,000,	125,000 psi
Uniform elongation	1.4%,	1.4%
Total elongation	3.3%	3.1%

A typical Zircaloy-2 fuel clad specification would call for the following room temperature properties (unirradiated):

Ultimate tensile strength	-	70,000 psi (min)
0.2% yield strength	-	60,000 psi (min)
Elongation in 2" (min)	-	16%

These results on Monticello BWR indicate that at room temperature the properties of irradiated Zircaloy fuel cladding ($\sim$44,000 MDW/MT) in the axial direction retain good ductility and exhibit significantly increased tensile strength. The combination of strength and ductility are considered adequate for spent fuel handling of these assemblies.

For the PWR, Monticello [3], post-irradiation examination was performed on three spacers after bundle average burnups of 42,000 or 45,600 MWD/MT. The Zircaloy-4 spacer material had a uniform oxide thickness up to 45 µm. Some nodular oxide was found up to 130 µm thick but the overall amount of nodular oxide was considered small. The average hydrogen content had a high value of 121ppm.

Tensile tests were run on the spacer material at 288^{o}C. For the lower fluence of 6.7 x 10^{21} n/cm^{2} (E>1MeV) the average of 6 specimens was ultimate tensile strength $\sim$ 92,000 psi, 0.2% yield $\sim$ 86,000 psi.

For the higher fluence (11 x 10^{21} n/cm^{2}, (E>1MeV) ultimate tensile strength was $\sim$ 98,000 psi and the 0.2% yield $\sim$ 90,000 psi.

The uniform elongation was $\sim$ 1.9% for both fluence levels. The total elongation was an average of 7.8% for the lower flux level and 7.2% for the higher flux.

Tensile data on the spacer Zircaloy-4 was not given for the Monticello material at room temperature. The 288^{o}C data (and other data relating to Zircaloy room temperature and elevated temperature properties) do indicate that sufficient strength and ductility should be present at lower temperatures for safe handling of these BWR assemblies after extended burnup and storage in the pools.

IV. Conclusions

After five cycles of irradiation (~ 55,000 MwD/MtU) PWR fuel assembly Zircaloy-4 thimble tubes, which support the structure during handling, demonstrated low corrosion and hydrogen uptake and sufficient ductility to permit safe post-irradiation handling.

The Zircaloy spacers under visual examination showed no evidence of mechanical deterioration or unusual corrosion that would adversely affect fuel handling.

In test BWR fuel bundles exposed to 45,600 MwD/MtU, low corrosion and hydrogen uptake was found in the fuel clad. The post irradiation examination showed the bundles and fuel rods were in good condition for the high exposures achieved.

The Zircaloy-2 clad had sufficient strength and residual ductility to withstand fuel handling. The Zircaloy-4 spacer material, after comparable exposures showed low oxidation and low hydrogen pickup and good ductility when tested at 288^{o}C. This spacer material should provide adequate support during handling after high burnup and pool storage.

On the basis of the available data, both PWR and BWR assemblies should present no problems related to the strength of their main structural components for handling in the pool or during back-end handling after burnups up to 45,000 MwD/Mt.

REFERENCES

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2. "Review of Swedish Work on Irradiation Effects in Canning and Core Support Materials," M. Grounes, ASTM-STP 426, June 1966.

3. BWR Fuel Bundle - Extended Burnup Program Technical Progress Report - GEAP-30643-May, 1984

4. Physical Metallurgy - Chalmers - John Wiley & Sons - 1959 pg. 218.

TABLE A-1

ZION THREE-AND FIVE-CYCLE SKELETON OXIDE FILM THICKNESS IN THIMBLE TUBE

Span No.	Distance from Bottom of Fuel (inches)	No. of Cycles	Oxide Film Thickness (mils) Outer Surface Mean	Outer Surface Std Dev	Inner Surface Mean	Inner Surface Std. Dev
2	50	3	0.17	0.01	0.16	0.01
		5	0.19		0.19	
3	76	3	0.17	0.01	0.16	0.02
		5	0.20		0.19	
5	128	3	0.16	0.01	0.16	0.01
		5	0.20		0.20	
6	147	3	0.29	0.01	0.39	0.02
		5	0.43		0.43	

TABLE A-2

ZION THREE-AND FIVE-CYCLE SKELETON
HYDROGEN CONCENTRATION IN THIMBLE TUBE

Span No.	Distance from Bottom of Fuel (inches)	Hydrogen Concentration[a] (ppm) 3-Cycle	5-Cycle
2	50	49	66
3	76	42	53
5	128	36	73
6	147	63	178

a. Estimated measurement uncertainty plus or minus 2 ppm

TABLE A-3

RESULTS OF TENSILE TESTS ON THIMBLE TUBE SAMPLES

Property Measured	Nonirradiated Avg[a]	No. of Cycles	Irradiated Samples From Span 2	Span 3	Span 5	Span 6
0.2% Yield Strength	58.7	3	129.3	130.4	128.5	126.8
(ksi)		5	128.6	129.3	127.7	125.1
Ultimate Strength	81.0	3	137.7	137.2	136.7	130.4
(ksi)		5	139.3	140.7	140.5	137.5
Fracture Strength (ksi)	3	131.1	130.2	131.9	124.6	
		5	132.4	130.1	133.2	126.4
Uniform Elongation (%)		3	2.6	4.9	4.6	1.9
		5	5.3	5.1	5.8	3.0
Total Elongation (%)	33.9	3	4.5	7.8	6.7	2.2
		5	7.3	6.3	8.0	4.6

a. Average of all test sasmples representing thimble tubes used in Zion first core loading (approximately 40 tubing lots)

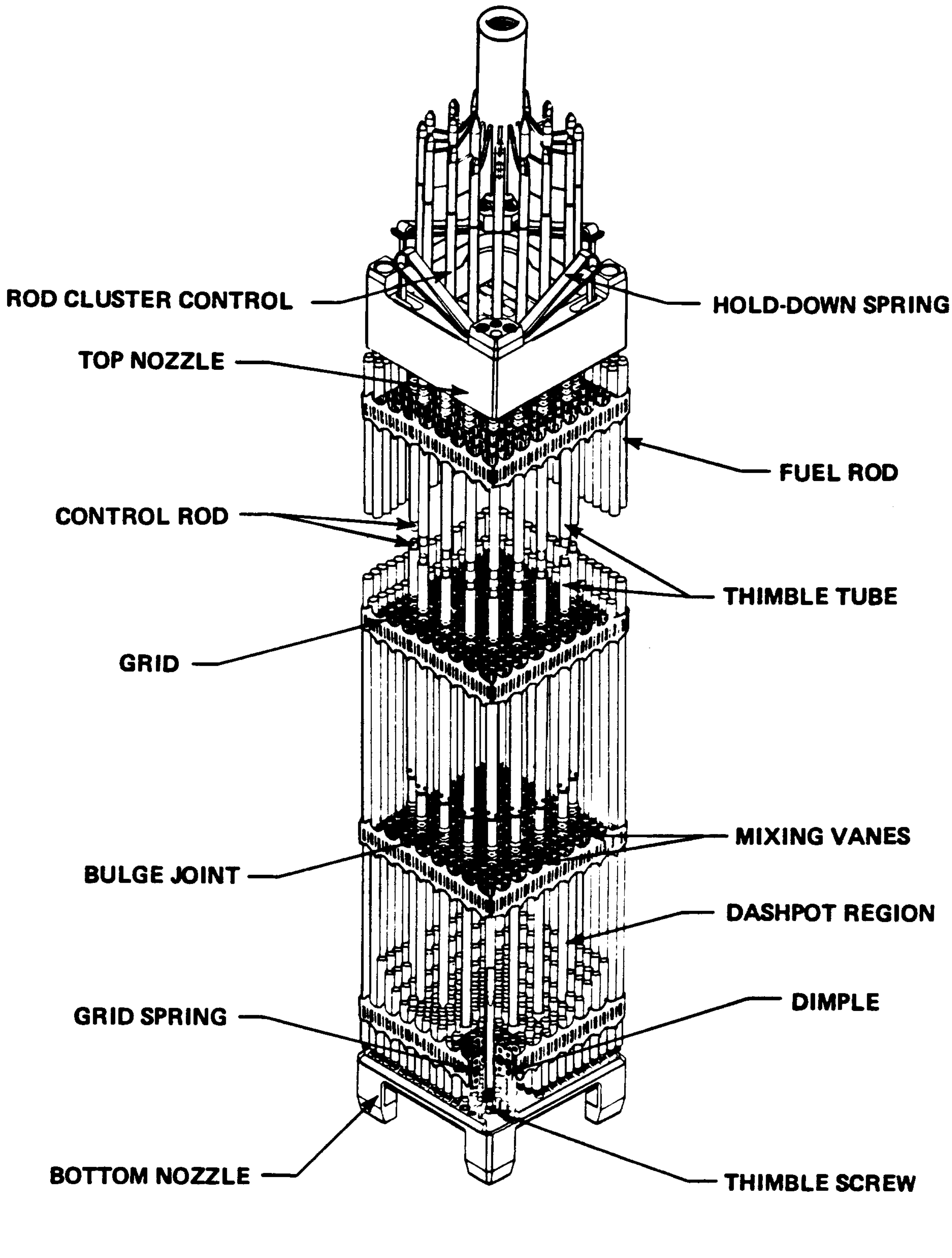

Figure A-1. Westinghouse RCC Fuel Assembly

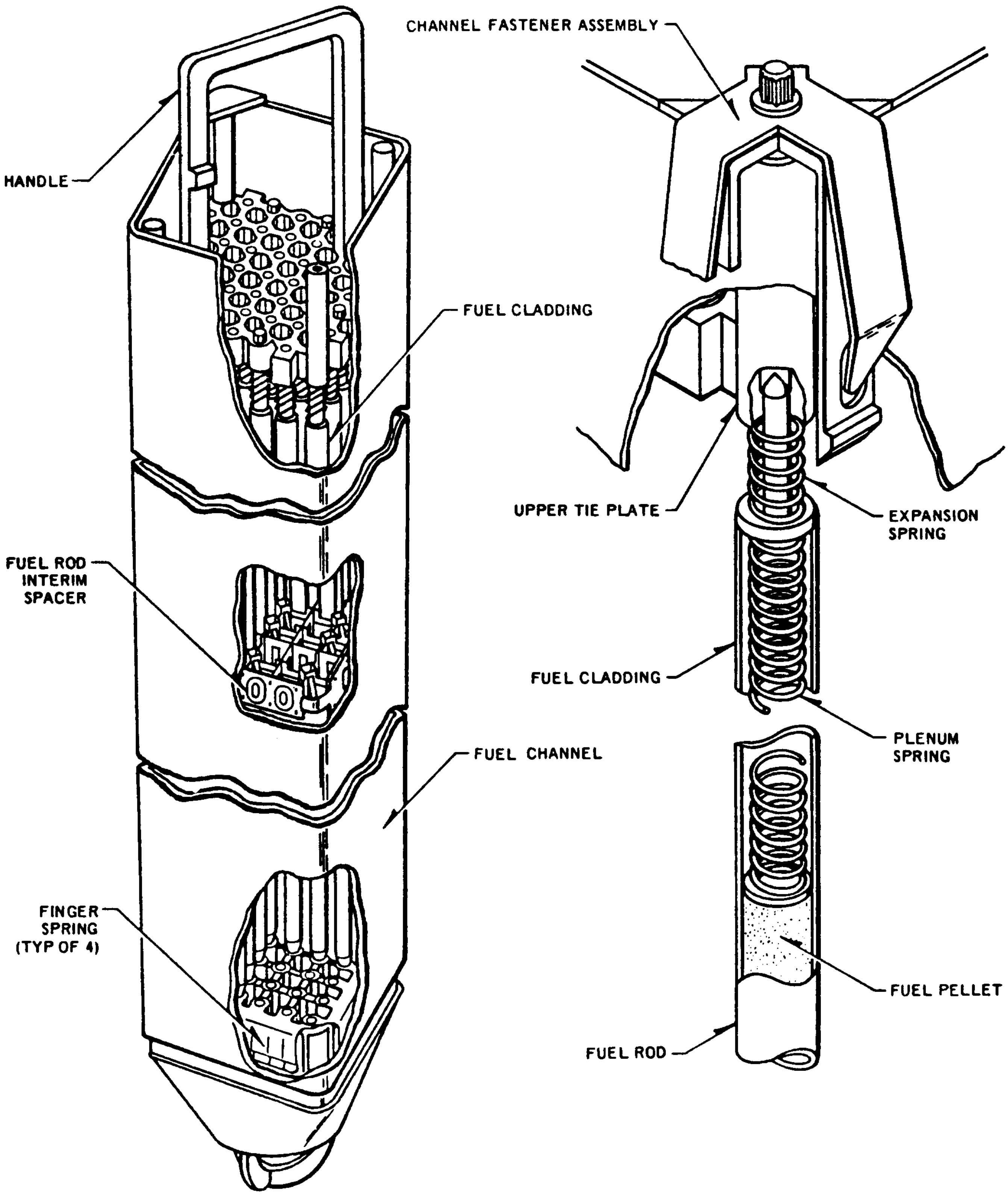

Figure A-2. Fuel Assembly--Isometric

APPENDIX 3

FUEL CYCLE COST METHODOLOGY
THE BASIC EQUATIONS

A. Definitions and Assumptions

The evaluation procedure for determining the economic merit of a proposed fueling program for a nuclear reactor is based on the following assumptions:

1. The reactor operates with a core made-up of, $4m_o+a$, fuel assemblies and a thermal-to-electric conversion efficiency of, η. A quantity of reload fuel assemblies is inserted at each refueling.

If, at the beginning of a new cycle 4m reload fuel assemblies are loaded, then of these, the number $4m_1-a$ stay in-core for N cycles and the number $4m_2+a$, stay in-core for (N+1) cycles.

A cycle lasts for a prescribed period during which the reactor is assumed to run at some prescribed fraction of full power. During the cycle, all fuel assemblies are assumed to increase in burnup by the cycle average.

The fuel that stays in-core for N cycles, ("Short Fuel"), has a charge enrichment E_1. Of the fuel that stays in-core for (N+1) cycles, "a" fuel assemblies are at enrichment E_1 and the rest are at enrichment E_2, which is usually higher than E_1 but may be the same.

The quantities defined above are related to each other for each cycle, as follows:

$$m_1 + m_2 = m$$

$$N + \frac{m_2}{m} = \frac{m_o}{m}$$

where N and m_2/m are, respectively, the integer part and the fractional part of m_o/m. Thus N and m_2 are uniquely determined by m.

2. Each new fuel assembly contains, h, KgU. The cost of each fuel assembly is Q=U+C+S+F, and is calculated under the following assumptions:

   a. Uranium is paid for at a time, t_1, years before in-core use. The total cost is U.

   b. Conversion is paid for at a time, t_2, years before in-core use at a total cost of C. The uranium loss in conversion is, L_c.

   c. Enrichment is carried out at a tails assay of, E_t, and is paid for, t_3, years before in-core use. The total cost is, S.

   d. Fabrication is paid for, t_4, years before in-core use at a total cost of F. The uranium loss in fabrication is, L_f.

   e. A waste disposal assessment of, either 1$/MWhr(e) or $250/kgU or a combination of the two is levied against power production.

   It is clear that the cost of each batch will be QM.

3. A continuous cost treatment is used, including continuous discounting of all costs to the begining of the year 1985. This is assumed to be when the initial core, (the new batch) is placed in service.

4. Each batch investment ("rate base") is depreciated in proportion to its actual or nominal energy production during each cycle. The unrecovered investment earns money at the rate, i, defined by

$$i = i_e + i_d$$

where

i_e = \$/yr paid to equity holders per \$ of rate base

i_d = \$/yr paid to bond holders per \$ of rate base

5. During the period before its in-core use any payments made to produce a fuel batch are added to the rate base and earn at the rate, i.

6. A tax at the rate, r, is paid on net income. When a new fuel batch is placed in service an investment tax credit amounting to the fraction, f, of the initial investment is taken. The associated special tax depreciation is used. This is defined by:

Tax depreciation obtained in year, n, after start of service $= FC_n \cdot$(Initial Investment), $n = 1, 2, 3, 4, 5$.

where

$$F = 1 \quad \text{for} \quad f = 0.08$$

$$= 0.95 \quad \text{for} \quad f = 0.1$$

$$C_1 = 0.15$$

$$C_2 = 0.22$$

$$C_3 = C_4 = C_5 = 0.21$$

7. Normalized accounting is used. The investment tax credit is removed from the rate base. Also removed is the change in income tax paid due to the use of the special tax depreciation instead of book depreciation for tax purposes.

8. Two money rates will be used in addition to those defined in paragraph 4 and 5 above. The "cost of working capital", i_w, is defined as the pre-tax rate which will yield the desired return, i, after taxes:

$$i_w = i_d + \frac{i_e}{1-r}.$$

The "tax-adjusted" cost of money is defined by

$$i_a = (1-r)\, i_d + i_e,$$

$$= (1-r)\, i_w.$$

The tax-adjusted cost of money is frequently used as the discount rate in present worth analyses. It will be used here.

B. General Relations

Let

$R(t)dt$ = Revenue required for a batch over the time interval, dt, at time t.

$I(t)$ = Unrecovered investment for the batch at that time.

$D(t)dt$ = Corresponding reduction in rate base

$D_o(t)dt$ = Book depreciation

$\Delta(t)dt$ = Tax depreciation

$T(t)dt$ = Income tax paid

$W(t)dt$ = Waste disposal assessment

$\delta(t)$ = The Dirac delta function. This is introduced in order to simplify the presentation. It is defined as a function which vanishes for all values of t except for t=0, where it is infinite in such a way that $\int \delta(t)\, dt = 1$.

Then

$$\frac{dI}{dt} = -\, D(t), \qquad (1)$$

from the definition of D(t). This depreciation is equal to:

	the book depreciation	=	$D_o(t)$;
plus:	the investment tax credit	=	$fQM\delta(t)$;
plus:	the tax "savings" due to the use of the Special tax depreciation	=	$r(\Delta(t) - F\ D_o(t))$
less:	the normalization payment made to recover the investment tax credit for the rate payers	=	$-f\ D_o\ (t)$.

$$D(t) = D_o(t) + fQM\delta(t) + r(\Delta(t) - FD_o(t)) - f\ D_o(t),$$

$$D(t) = (1-f-rF)\ Do(t) + fQM\delta(t) + r\ \Delta(t), \tag{1a}$$

$$\frac{dI}{dt} = -\ (1-f-rF)D_o(t) - fQM\delta(t) - r\Delta(t).$$

Integrating this equation from t = o gives

$$I(t) - I(o) = -\ (1-f-rF)\int_o^t D_o(u)du - fQM - r\int_o^t \Delta(u)du,$$

or since

$$I(o) = QM$$

$$I(t) = (1-f)QM - (1-f-rF)\int_o^t D_o(u)du - r\int_o^t \Delta(u)du. \tag{2}$$

The tax paid per unit time will be

$$T(t) = r\ (R(t) - W(t) - i_d I(t) - \Delta(t)) - fQM\delta(t), \tag{3}$$

where tax deductions "above the line" have been taken for the operating expense, $W(t)$, the interest, paid $i_d I(t)$, the allowed depreciation, $\Delta(t)$, and "below the line" for the investment tax credit, $fQM\delta(t)$. The revenue required is given by the expression

$$R(t) = D(t) + iI(t) + T(t) + W(t). \qquad (4)$$

Substituting (2) and (3) into (4) and simplifying leads to

$$R(t) = \left(\frac{1-f-rF}{1-r}\right).\ D_o(t) + i_w I(t) + W(t). \qquad (5)$$

Substituting equation (2) into equation (5) gives

$$R(t) = \left(\frac{1-f-rF}{1-r}\right).D_o(t)+W(t)+i_w\{(1-f)QM-(1-f-rF)\int_o^t D_o(u)du-r\int_o^t \Delta(u)du\}. \qquad (6)$$

Equation (6) is applicable to any batch.

The book depreciation may be written in the form

$$D_o(t) = QMg_1(t),$$

where $g_1(t)$ is a normalized book depreciation function which vanishes for $t<o$ and for $t>(N+1)a$ and for which

$$\int_{-\infty}^{\infty} g_1(t)dt = \int_o^{(N+1)a} g_1(t)dt = 1$$

The tax depreciation may be written

$$\Delta(t) = FQMg_2(t)$$

Where in the special case that the investment tax credit is taken, $g_2(t)$ is a normalized function given by

$$g_2(t) = \begin{cases} .15 & o<t<1 \\ .22 & 1<t<2 \\ .21 & 2<t<5 \\ 0 & \text{for all other values of } t. \end{cases}$$

If the investment tax credit is not taken and the book depreciation is used for the tax depreciation then $g_2(t) = g_1(t)$.

Using the above representation for D_o and equation (6) may be written

$$R(t) = \left(\frac{1-f-rF}{1-r}\right) QMg_1(t)+W+i_w\{(1-f)QM-(1-f-rF)QM(1-G_1(t))-rFQM(1-G_2(t))\}$$

where

$$G_i(t) = \int_t^{\infty} g_1(u)du$$

and a similar definition applies for $G_2(t)$.

Grouping together the terms with QM as a multiplier gives

$$R(t) = \gamma QMH(t) + W(t),$$

where

$$H(t) = g_1(t) + i_a \left(G_1(t)+\left(\frac{rF}{1-f-rF}\right) . G_2(t)\right)$$

$$\gamma = \frac{1-f-rF}{1-r} .$$

C. Present Worth of Revenue Requirements of a Batch Basis

At a discount rate, j, the present worth of revenue requirements, including the working capital costs prior to in-core use will be

$$P_b = Q'M + \int_0^\infty e\text{-}jt \; R_b(t)dt$$

$$P_b = Q'M + \int_0^\infty e^{-jt}dt \; (QM\gamma H(t) + W(t)),$$

$$P_b = Q'M + QM \int_0^\infty e^{-jt} H(t)dt + V(j) \qquad (18)$$

where

$$Q' = U(e^{jt_1}-1) + C(e^{jt_2} 1) + S(e^{jt_3} 1) + F(e^{jt_4}-1)\frac{i_w}{j} \qquad (19)$$

and

$$V(j) = \int_0^\infty e^{-jt} W(t)dt$$

are the present worth of working capital costs prior to in-core use for a fuel assembly, and the present worth of spent fuel disposal assesment costs, respectively.

The discounted values of the normalized depreciation functions are defined by:

$$L_1(j) = \int_0^\infty e^{-jt} g_1(t)\, dt,$$

$$L_2(j) = \int_0^\infty e^{-jt} g_2(t)\, dt.$$

It may be shown that

$$\gamma\int_0^\infty e^{-jt}H(t)dt = \frac{iw}{j}(1-f) + \gamma L_1(j)\left(1-\frac{ia}{j}\right) - rF\frac{iw}{j}L_2(j)$$

and hence the expression for P_b becomes:

$$P_b = Q'M+QM \left((1-f) \frac{i_w}{j} + \gamma \left(1- \frac{i_a}{j}\right) L_1 (j) - \frac{rFi_w L_2{}^{(j)}}{j} \right) + V(j) \zeta M \; bL \; (j-\psi) \tag{20}$$

Equation (20) is an explicit expression for the present worth to the time of loading of all revenue requirements associated with the batch.

Introducing the quantity Z(j) defined by,

$$Z(j) = (1-f) \frac{(iw)}{j} + \gamma \frac{(1-ia)}{j} L_1 (j) - \frac{rFi_w L_2 (j)}{j} \tag{20a}$$

then

$$\frac{(1-ia)}{j}$$

$$P_b = Q'M + QMZ(j) + \xi M_c L_1(j)$$

The dominant cost component in equation (20a) is the middle term. In this term the factor

$$QM,$$

represents the effective initial capital investment in the new fuel charge. The other factor,

$$Z(j),$$

represents the combined effects of depreciation of the original investment, return on the outstanding capital, and the associated income taxes. It is a remarkable fact that if $j = i_a$, then under normal circumstances, such as use of full tax benefits, the quantity Z (j) will be a constant, independent of the fuel management details.

In this case the value of P_b will be largely determined by the initial cost of the fuel charged and there will be no dependence upon how long the fuel stays in the core.

In the event that income tax benefits are not taken then

$$f = o, \ F = 1, \ g_2(t) = g(t),$$

and the general batch equation reduces to

$$P_b = Q'M + QMZ_1(j) + M_o bL_1(j) \quad (20d)$$

with

$$Z_1(j) = \frac{iw}{j} + (1 - \frac{iw}{j})\ L_1(j) \quad (20e)$$

The quantity $Z_1(j)$ will vary more strongly with the depreciation schedule than does $Z(j)$. This is largely due to the multiplier $(1 - \frac{iw}{j})$ instead of $(1 - \frac{ia}{j})$ on $L_1(j)$. For most evaluations the discount rate, j, will be in the range

$$i_a \leq j < i_w$$

Thus the factor multiplying L_1 (j) will generally be positive in Z (j) and negative in Z_1 (j) so that there will be opposite tendencies in the two cases as the fuel burnup is increased.

TIC-4500 UC-78 (164 Copies)

Mr. Tony Mansell
Arkansas Power and Light Company
P.O. Box 551
Little Rock, AR 72203

Mr. H. Hassan
Nuclear Power Generation Division
Babcock and Wilcox Company
P.O. Box 1260
Lynchburg, VA 24505

Mr. Thomas A. Coleman
Nuclear Power Generation Division
Babcock and Wilcox Company
P.O. Box 1260
Lynchburg, VA 24505

Mr. Rick Bold
Battelle-Pacific Northwest Laboratory
215 13th Avenue E. #8
Seattle, WA 98102

Mr. M. S. Freshley
Battelle-Pacific Northwest Laboratory
Battelle Boulevard
P.O. Box 999
Richland, WA 99352

Mr. B. H. Ruth
Bettis Atomic Power Laboratory (W)
P.O. Box 79
West Mifflin, PA 15122

Mr. John LaVake
Combustion Engineering, Inc.
1000 Prospect Hill Road
P.O. Box 500
Windsor, CT 06095

Mr. R. N. Duncan
Combustion Engineering, Inc.
1000 Prospect Hill Road
P.O. Box 500
Windsor, CT 06095

Dr. D. O'Boyle
Commonwealth Edison Company
P.O. Box 767
Chicago, IL 60690

Dr. Min L. Lee
Chief Nuclear Engineer
Consolidated Edison Company of New York, Inc.
4 Irving Place
New York, NY 10003

Mr. Tom Hollowell
Consumers Power Company
1945 West Parnell Road
Jackson, MI 49201

Mr. D. B. Wehmeyer
Detroit Edison Company
2000 Second Avenue
Detroit, MI 48226

Mr. J. D. Kortheuer
Duke Power Company
P.O. Box 33189
Charlotte, NC 28242

Mr. Philip E. MacDonald
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415

Dr. David Franklin
Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303

Dr. Keith N. Woods
Exxon Nuclear Company, Inc.
2101 Horn Rapids Road
Richland, WA 99352

Dr. Leo Van Swam
Exxon Nuclear Company, Inc.
2101 Horn Rapids Road
Richland, WA 99352

Dr. H. S. Rosenbaum
Nuclear Energy Division
General Electric Company
175 Curtner Avenue
San Jose, CA 95125

Dr. H. W. Schadler, Manager
Metallurgy Laboratory
General Electric Company
Research and Development Center
P.O. Box 8
Schenectady, NY 12301

Mr. Gordon Bond
GPU Service Corp.
260 Cherry Hill Road
Parsippany, NJ 07054

Mr. A. T. Muccigrosso
Knolls Atomic Power Laboratory
Box 1072
Schenectady, NY 12301

Mr. William J. Tunney
Long Island Lighting Company
175 East Old Country Road
Hicksville, NY 11801

Mr. R. G. Ballinger
Massachusetts Institute of Technology
Room 8139
77 Massachusetts Avenue
Cambridge, MA 02139

Professor Michael Driscoll, NW13-201
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

Mr. Charles Tyrone
Mississippi Power and Light
P.O. Box 1640
Jackson, MS 39205

Mr. S. W. Wilczek, Jr.
Niagara Mohawk Power Corporation
300 Erie Boulevard West
Syracuse, NY 13202

Mr. Roger O. Anderson
Northern States Power, G08
414 Nicollet Mall
Minneapolis, MN 55401

Dr. Dennis Coleman
Nuclear Associates International
6003 Executive Boulevard
Rockville, MD 20852

Mr. Peter A. Aucoin
Nuclear Assurance Corporation
5720 Peachtree Parkway
Norcross, GA 30092

Mr. Richard Lobel
Core Performance Branch
Nuclear Regulatory Commission
MS P-924
Washington, DC 20555

Mr. Melvin Silberberg
Chief, Fuel Behavior Branch
Nuclear Regulatory Commission
MS 1130SS
Washington, DC 20555

Dr. Richard Jaworski
Omaha Public Power District
1623 Harney
Omaha, NE 68102

Mr. G. F. Daebeler
Philadelphia Electric Company
2301 Market Street
P.O. Box 8699
Philadelphia, PA 19101

Mr. B. H. Koske
Energy Conversion Engineer
Public Service Company
of New Mexico
P.O. Box 2267
Albuquerque, NM 87103

Mr. Kashmiri L. Mahna
Public Service Electric
and Gas Company
P.O. Box 570, Room 3347
Newark, NJ 07101

Professor A. Sesonske
School of Engineering
Purdue University
West Lafayette, IN 47907

Mr. Roger Powers
Sacramento Municipal Utility District
6201 S Street
P.O. Box 15830
Sacramento, CA 95852

Professor A. K. Miller
Department of Materials Science
and Engineering
Stanford University
Stanford, CA 94305

W. A. Franks (10)
L. Geller
S. M. Stoller Corporation
1250 Broadway
New York, NY 10001

Mr. Philip D. Brown
Nuclear Engineer
Fuel Cycle Services
Tennessee Valley Authority
409 Krystal Building
Chattanooga, TN 37401

Mr. David Dziadosz
Virginia Electric and
Power Company
P.O. Box 26666
Richmond, VA 23261

Mr. D. L. Larkin
Washington Public Power Supply
System
P.O. Box 968
Richland, WA 99352

Mr. R. S. Miller
Nuclear Fuel Division
Westinghouse Electric Corporation
P.O. Box 3912
Pittsburgh, PA 15230

Dr. Elwyn Roberts
Manager, Irradiation Testing
Westinghouse Electric Corporation
P.O. Box 3912
Pittsburgh, PA 15230

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